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GEOLOGICAL MAGAZINE

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The Hecla Hoek Succession in Ny Friesland, Spitsbergen

By W. B. HARLAND and C. B. WILSON

ABSTRACT

A stratigraphical outline of the Hecla Hoek succession summarizing post-war work in Ny Friesland is presented for the first time. This shows a geosynclinal series of sediments reaching down at least 15,000 m. below Cambrian in a more or less continuous succession. It is compared with other Hecla Hoek successions in Svalbard.

I. INTRODUCTION

THE Hecla Hoek Formation was first named (Hecla-Hook) by A. E. Nordenskiöld (1863) from Mt. Hecla (now Heclahuken), after H.M.S. Hecla of Parry's North Polar Expedition in 1827 which wintered beside this mountain in Sorgfjorden (then Treuenberg Bay). Something of the rocks was already known from Horner's description (1860) of Parry's material, and Blomstrand (1864) supplemented Nordenskiöld's observations with a more detailed traverse in the same latitude (80° N.).

Subsequently all the ancient (pre-Devonian) rocks in the whole of Svalbard came to be given the same name (Orvin 1940, p. 8). These included unfossiliferous rocks, often deformed or even metamorphosed, which are of unproven age. Then Sandford (1950) demonstrated a more ancient complex juxtaposed to unmetamorphosed Hecla Hoek sediments. The problem of distinguishing a succession within each area and of correlating with other areas has recently been attacked in several places.

Ny Friesland, which includes the original type area in the north, has remained relatively unknown. Rocks and structures in this area have been described by De Geer (1923), Tyrrell (1922), Fairbairn (1932) and Harland (1941), but the only stratigraphical accounts are those of Odell (1927), Kulling (1932 and 1934) whose main work was, however, in Nordaustlandet, and Fleming and Edmonds (1941). The last of these accounts admirably summarizes the published investigations to date.

As a result of a series of Cambridge reconnaissance expeditions investigating the structure of Ny Friesland, the broad outlines of the

succession have emerged. The detailed discussion of stratigraphy is bound up with the petrology, and also in several regions with the structural interpretation ; but it is hoped that this stratigraphical account published in advance of the separate local descriptions will prove useful.

The succession as we find it is broadly in accordance with that described in Nordaustlandet by Kulling (1934), especially in the upper part. Lower down, however, there are several uncertainties of correlation and identity and it seemed better to propose a new series of stratigraphical names based entirely on our own observations. In so doing we have named series and formations from localities in southern Ny Friesland where the rocks are well exposed. Text-fig. 1 shows the place-names so used, but a geological map of this complex structure must await a larger scale in a tectonic paper.

The succession proposed lies between known successions in Nordaustlandet and south-west Svalbard. It seems to be both thicker and more complete than proved elsewhere. This paper will begin, therefore, by outlining the proposed succession and then comparing it with published descriptions, so as to avoid at the outset somewhat indeterminate discussions of identity and correlation. This order should not obscure the debt inevitably owed to earlier work.

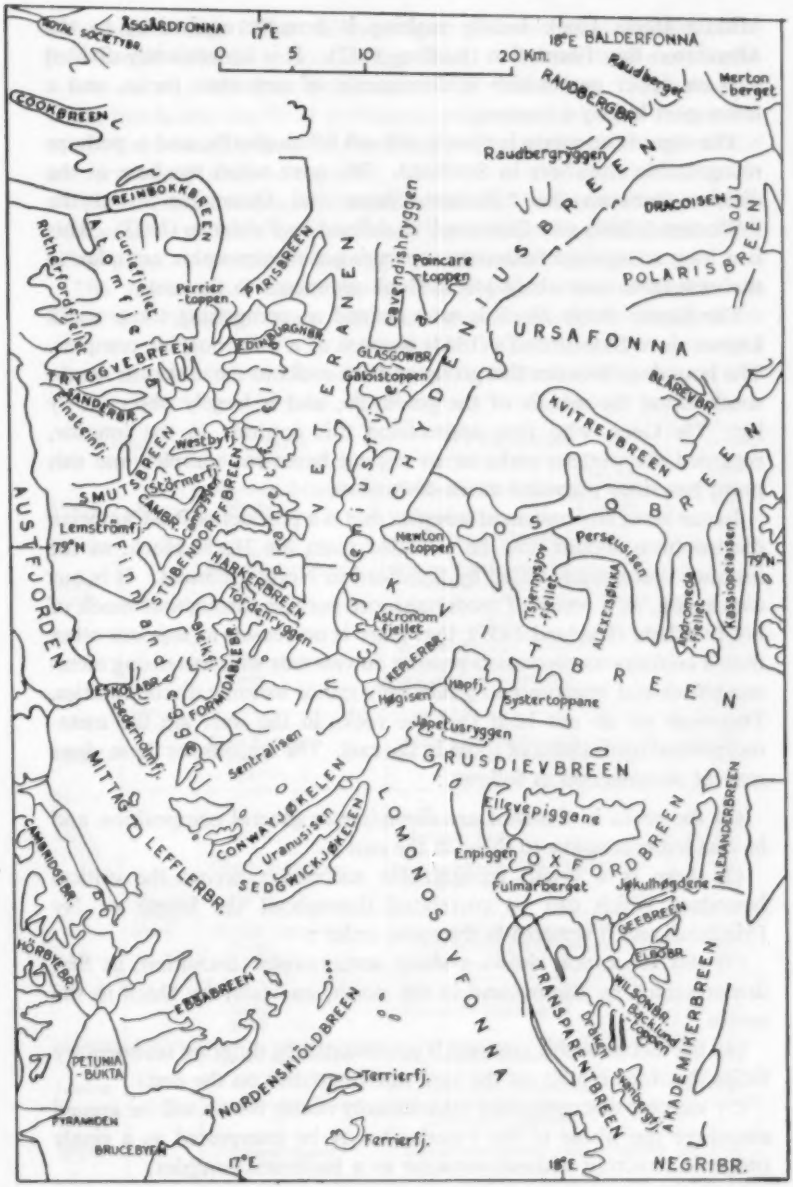
II. The Hecla Hoek Complex in Ny Friesland

Hecla Hoek rocks were first described in Ny Friesland, which peninsula now seems to contain a very thick and reasonably continuous succession. We propose to divide it into three broad groups : Upper, Middle and Lower Hecla Hoek.

The Upper Hecla Hoek includes any rocks taken to be at least pre-orogenic pre-Downtonian down to and including the tillite-bearing deposits which are of great value in Eo-Cambrian correlation, even when metamorphosed. Further division of the Upper Hecla Hoek will depend on the usual methods in Lower Palaeozoic stratigraphy.

Ordovician faunas had long been known from Bjørnøya (Holtedahl 1920). Similar faunas as well as some of Lower Cambrian age have recently been discovered in southern Spitsbergen (Major and Winsnes 1955). In north-eastern Spitsbergen the only dated fossils are probably Lower Cambrian brachiopods (Kulling 1934) from Nordaustlandet. Our expeditions of 1953 and 1955 found Lower and ?Upper Cambrian faunas in Ny Friesland within the top 1,000 m. of the exposed succession. Previously these rocks were only known to be older than a pre-part Carboniferous orogeny.

The Middle Hecla Hoek continues downwards without any major break. The terms Eo-Cambrian and Algonkian are difficult to apply precisely in international correlation and it is preferred to define the



TEXT-FIG. 1.—Place-name map of southern Ny Friesland (with localities from which stratigraphical names have been proposed). Places in northern Ny Friesland mentioned here will be found on the map on p. 416 of Fleming and Edmonds paper (1941).

Middle Hecla Hoek locally making it broadly equivalent to the Murchison Bay Formation (Kulling 1932). It is conveniently divided into an upper part which is dominantly of carbonate facies, and a lower part largely quartzose.

The top of the group is clearly defined lithologically, and is perhaps recognizable elsewhere in Svalbard. We have taken the base at the division between the " Eastern Slates and Quartzites " and the " Western Schists and Gneisses " as defined by Fairbairn (1933). This is a long recognized boundary separating a metamorphic complex to the west from undoubted Hecla Hoek sediments to the east.

The Lower Hecla Hoek is now defined as comprising those rocks known since Blomstrand's (1864) account as a metamorphic complex. The boundary between this group and the rocks to the east runs north-south along the middle of the peninsula, and is largely obscured by ice. De Geer, who first appreciated this contrast in the interior, regarded the western rocks as an ancient basement complex and this point has since provided much discussion.

In our view, any basement complex that is a product of Pre-Cambrian diastrophism should now be excluded from the Hecla Hoek, as for instance that demonstrated by Sandford in Nordaustlandet. It is our conclusion, as a result of reconnaissance surveys throughout much of Ny Friesland (Harland 1955), that there is no reason to suppose other than a continuous succession passing downwards with increasing metamorphism and interrupted by relatively minor tectonic discontinuities. Therefore we do not hold that the rocks in the west are the metamorphosed equivalents of those in the east. The reasons for these views may be summarized as follows :

(1) the rocks in the west are dissimilar in general composition and in detailed succession to those in the east ;

(2) there is a broad recognizable succession across the critical boundary which can be correlated throughout the length of Ny Friesland, and it remains in the same order ;

(3) this succession shows a sharp metamorphic transition, as first demonstrated by Blomstrand in the north, and later by Odell in the centre ;

(4) the metamorphic contrast is accentuated by differing sedimentary facies (between schists on the west and quartzites on the east) ;

(5) tectonic discontinuities undoubtedly occur, but as will be argued elsewhere the whole of Ny Friesland may be interpreted as a single orogenic structure without recourse to a basement complex.

The absence of a basement complex has not been proved at the surface in Ny Friesland, and it might yet lie to the west amongst gneisses whose relationships to the main structure have yet to be determined.

A characteristic feature of the largely sedimentary succession is the presence of rocks of igneous composition. Of these, layers of amphibolite are very widespread throughout the succession. Some amphibolite bands are clearly of pyroclastic origin, and it seems reasonable to attribute many others to the same origin, while lavas and related intrusives may also be expected.

Gneisses of granitic composition, which also lie concordantly or even conformably with the sediments, are more difficult to interpret. They either inject or transform the original sedimentary quartzites.

The *Hecla Hoek succession* in Ny Friesland is summarized in Table 1. Although many members can be traced throughout the

TABLE I. THE HECLA-HOEK SUCCESSION IN NY FRIESLAND

Group		Series	Formations	Thickness (in metres)
UPPER HECLA HOEK (1760)		Oslobreen Series 940 m.	Oslobreen Limestones { Upper / Middle / Lower	400 / 150 / 200
			Oslobreen Dolomites	180
			Oslobreen Sandstone	12
		Polarisbreen Series 830 m.	Upper Polarisbreen Shales	280
			Polarisbreen Tillite Formation	280
			Lower Polarisbreen Shale Formation.	270
MIDDLE HECLA HOEK (7250)	Upper Middle Hecla Hoek	Akademikerbreen Series 1,100 m.	Backlundtoppen Dolomites	250
			Backlundtoppen Oolites	250
			Draken Conglomerates	300
			Svanbergfjellet Beds	ca. 300
		Grusdievbreen Series 800 m.	Upper Grusdievbreen Limestones	ca. 600
			Lower Grusdievbreen Limestones	200
	Lower Middle Hecla Hoek	Oxfordbreen Series 460 m.	Fulmarberget Shales	ca. 60
			Enpiggen Beds	ca. 400
		Upper Veteranen Series 800 m.	Glasgowbreen Greywackes	440
			Glasgowbreen Quartzite	360
		Middle Veteranen Series 1,550 m.	Cavendishryggen Quartzites	300
			Cavendishryggen Limestones	250 +
			Galoistoppen Beds	ca. 1000
		Lower Veteranen Series 2,500 + m.	Veteranen Quartzites	2150 +
			Veteranen Limestones	ca. 350
LOWER HECLA HOEK		Planetfjella Series	Planetfjella Schists	ca. 1000
		Harkerbreen Series	Tordenryggen Quartzites	ca. 1000
			Bleikfjellet Quartzites (with Camryggen gneisses)	2–3000
		Finnlandveggen Series	Smutsbreen Schists (and Marbles)	ca. 1000
			Eskolabreen Gneisses	ca. 2000
Stratigraphical position uncertain :				
		Austfjorden Series	Austfjorden Gneisses and Cambridgebreen Gneisses	
		Sørbreen Series	Sørbreen Quartzites	

length of the peninsula, the type sections have been chosen from the southern half where a more complete succession is available.

IIa. The Upper Hecla Hoek

The Upper Hecla Hoek in Ny Friesland consists of the Oslobreen Series above and the Polarisbreen Series below.

The Oslobreen Series

This is only fully exposed in lower Oslobreen where a thickness of about 1,000 m. has been estimated. The top of the succession is obscured by overlying Carboniferous rocks. A relatively uniform series of predominantly carbonate rocks has been subdivided provisionally into five formations pending further palaeontological work.

The Upper Oslobreen Limestone consist largely of both thick-bedded and massive leopardstones together with normal carbonate conglomerates and pseudo-conglomerates. No fossils were found in a rapid traverse.

The Middle Oslobreen Limestones form a conspicuous unit of thick-bedded leopardstones interbedded with shaly limestones. A fossiliferous horizon discovered in 1955 yielded a fauna of trilobites, brachiopods and gasteropods which has not yet been determined. Professor W. B. R. King tentatively suggested upper Cambrian as the age of the trilobites.

The Lower Oslobreen Limestones are composed largely of leopardstones, but Collenia beds, cherty horizons, and normal carbonate conglomerates also occur in abundance.

The Oslobreen Dolomites are rather featureless bedded dolomites and dolomitic limestones with much conglomerate. There is a conspicuous band crowded with *Salterella*, first found in 1953 by Mr. M. J. O'Hara, and kindly identified by Dr. C. Poulsen as *Salterella* sp. ind. (cf. *S. rugosa* Billings). Isolated specimens have been found at other levels in the dolomites.

The Oslobreen Sandstone, which is a thin formation of white and brown sandstones, conspicuously separates the dolomites from the underlying shales. It might be regarded as the beginning of the Cambrian succession.

The Polarisbreen Series

This series consists mainly of dark paper shales which are divisible into three formations, the middle one being the precise equivalent of the Sveanor Formation of Kulling (1932). Although in Ny Friesland the tillite is largely confined to the middle formation, examples of similar rocks have also been found in the lower one. The whole series forms a stratigraphical unit and there is not yet any convincing evidence of an

unconformity within it, although as was observed by Kulling, there are many local variations.

The series extends from north to south Ny Friesland and good exposures are to be found in both Polarisbreen and Wilsonbreen in the south, where thicknesses can easily be measured.

The Upper Polarisbreen Shales are best exposed in Polarisbreen and Blårevbreen where they consist entirely of interbedded dark purple and green paper shales with subordinate thin bands of brownish-weathering impure sandstone and have a fairly constant thickness of 280 m.

The Polarisbreen Tillite Formation is very similar to the Sveanor Tillite described by Kulling. It differs only in two respects, firstly in that there is a greater proportion of the unbedded gritty facies in southern Ny Friesland, and secondly in that the boulder content in Ny Friesland differs widely from that in Nordaustlandet. Apart from these differences, Kulling's description would cover the tillites of both areas.

The boulders are mostly of upper Middle Hecla Hoek type limestones and dolomites, but the igneous and metamorphic types include principally a pink leucocratic granite, and subordinate amounts of intermediate orthogneiss, granitic gneiss, albite syenite, quartzite, mica schist, jasper, and very rare porphyry.

The Lower Polarisbreen Shale Formation is more varied than the upper shales, especially towards the base where black limestones and siltstones appear. A threefold sub-division into shales (containing the suspected varved mudstones at the top), black shaly limestones, and mixed beds with siltstones at the base, appears to hold throughout Ny Friesland.

IIb. The Middle Hecla Hoek
(upper part)
The Akademikerbreen Series

This series is ideally exposed in Akademikerbreen, but there are many other good exposures throughout Ny Friesland. The series includes all the rocks of Ryssö Dolomite type. The fourfold division is a natural one with the exception of the Svanbergfjellet beds which are not so well known, the junction with the Grusdievbreen Series only having been examined in one place.

The Backlundtoppen Dolomite is perfectly exposed on Backlundtoppen, as is the underlying oolite. This rock is almost certainly the equivalent of the original Ryssö limestone, later termed dolomite by Nordenskiöld (from Ryssøane, Hinlopenstretet), and consists of thoroughly massive, pinkish-white dolomite with abundant dolomite-breccia and *Collenia* structures, the laminae of which are silicified towards the top. The thickness varies from 250 m. in the south to about 150 m. in the north.

The Backlundtoppen Oolite is a dark formation of grey to black bedded limestones, mostly oolitic, with subordinate dark shales at the base. The limestone are often partly or wholly silicified. Some bands of pisolite occur high up, and at the top there is a zone of coloured oolites which is traceable throughout Ny Friesland, and which contains many beautiful examples of partly silicified oolites. The formation thins slightly northwards.

The Draken Conglomerates are almost certainly the equivalents of the Cherty Conglomerates of Odell, and also perhaps of the Black and White Chert Horizon. The best exposures are in southern Ny Friesland, notably in Akademikerbreen and Transparentbreen (Draken). The rocks are excellently, though thickly, bedded grey-white dolomite conglomerates and micro-conglomerates with conspicuous bands and lenticles of black chert which prove to be a local pene-contemporaneous replacement of the original rock. Although the formation is reduced in thickness from 300 m. in the south to 25 m. in the north, the character of the rocks is maintained.

The Svanbergfjellet Beds, unlike those above, are very variable, and include black limestones, *Collenia* dolomites (often ferruginous and partly silicified), pale cherty (non-conglomeratic) dolomite, black and vividly coloured dark paper shales as thin partings in the *Collenia* dolomite, and a few impure sandstones. The detailed stratigraphy and total thickness are still poorly known, the various sections being correlated in detail with difficulty. There seems to be a pronounced thinning to the north.

The Grusdievbreen Series

Only the lower part of the series is well known, and this part is well exposed in Grusdievbreen, Polarisbreen and Sorgfjorden in the north. The twofold division into a thick pale group overlying a thinner dark group is applicable everywhere, including apparently Nordaustlandet.

The Upper Grusdievbreen Limestones are banded pale grey and medium grey detrital limestones and dolomitic limestones. Distinctive sedimentary structures are not common and the rocks are very uniform. The thickness is uncertain, but is probably of the order of 600 m.

The Lower Grusdievbreen Limestones are dark grey-black detrital limestones, often silicified, and with considerable pyrite. Thin dolomitic bands weather paler brown, and are interbedded with the black limestone in an irregular manner. There are also a few cream weathering dolomite siltstones which disintegrate into very smooth flags. One example of *Collenia* has been found.

The Middle Hecla Hoek (cont.)

(lower part)

The lower part of the Middle Hecla Hoek comprises from top to

bottom the *Oxfordbreen, Glasgowbreen* and *Veteranen Series.* They may be regarded broadly as the equivalent of Fairbairn's (1933) " Eastern Slates and Quartzites ".

Unlike those above, these series are predominantly of quartzose rocks, often current-bedded, with only subordinate black limestones, and the total thickness is more than 5,300 m. It can be clearly shown that the alternating and repetitive nature of the strata is not to be explained by isoclinal folding of thin beds, but that extensive sections are broadly, though steeply, folded into regular anticlines and synclines which may be traced for many miles.

The Oxfordbreen Series

These beds are thought to be the equivalents of the Sålodd and Raudstup Formations of Nordaustlandet, and have been separated as a distinct series for this reason, although they do not seem to be an important unit in the Ny Friesland succession. The best exposures in the south are on Fulmarberget and Rogatsjevryggen, but these are imperfect.

The Fulmarberget Shales consist of pale purple and green weathering dolomitic shales (unlike the Upper Polarisbreen Shales), with subordinate quartzite. The formation has never been seen to exceed 60 m. in thickness, and often seems to be absent.

The Enpiggen Beds form a distinctive group of finely striped quartzose shales and flags, weathering to various dirty colours, and containing a few thin bands of white quartzite. The beds are well exposed on Enpiggen, west of Fulmarberget in Oxfordbreen, and their thickness in this area is about 400 m.

The Upper Veteranen Series

The series consists of alternating pale quartzites and dark greywackes, and is well exposed in several places including Japetusryggen and Glasgowbreen. The petrology of the rocks was described by Fairbairn (1933).

The Glasgowbreen Greywackes consist of two very similar greywackes separated by thick bedded quartzite (which thins out to the north).

The Glasgowbreen Quartzite is a uniform formation of pale, thickly bedded quartzites which forms a conspicuous band for many miles down Veteranen, northwards from Glasgowbreen.

The Middle Veteranen Series

This is a very mixed series of dark and medium-dark rocks, mainly dark quartzites, greywackes, shales and phyllites, but containing an important group of limestones—the Cavendishryggen Limestones. The whole is well exposed on Cavendishryggen and Galoistoppen and

elsewhere in Upper Veteranen, and no other sections have been measured.

The Cavendishryggen Quartzites, unlike the Glasgowbreen Quartzite, is a variable dark formation of impure fine grained quartzites with subordinate greywacke and shaly beds. The base is marked by a 30 m. band which contains four prominent bands of white quartzite.

The Cavendishryggen Limestones are made up of black flaggy limestones interbedded with dark flaggy and shaly quartzose beds, and towards the base with pale green phyllitic shales. The formation is readily distinguished from the Lower Grusdievbreen Limestones which are uniform and pure.

The Galoistoppen Beds make up a mixed formation of dark quartzites and greywackes together with pale green phyllitic shales and purple and green finely interbedded quartzose shales. These rocks are not very well known, and the type section on Galoistoppen has not been fully covered.

The Lower Veteranen Series

This is principally a quartzite formation which has been found well exposed in only one section in lower Veteranen. The thickness is at least 2,500 m. No detailed correlation has yet been made with the 600 m. of similar beds further up Veteranen (i.e. south along the glacier) where the upper boundary with Galoistoppen Beds remains to be proved. Moreover, uncertainty regarding the lower part of the succession leaves room for the possibility of a faulted contact with the Veteranen Limestones. The simplest sequence is provisionally assumed and in any case the limestones are sufficiently distinctive to warrant a separate formation.

The Veteranen Quartzites form a uniform sequence of thickly bedded dark coloured quartzites, largely purple and green, with only subordinate darker shaly bands. White quartzites become slightly more common towards the top. No further subdivision has been attempted and it is regarded provisionally as a single formation, although at least 2,150 m. thick.

The Veteranen Limestones consist principally of black flaggy limestones with orange weathering dolomitic bands interbedded with dark shales and quartzose flags. A thickness of 350 m. has been observed in the Lower Veteranen exposure, but elsewhere only about 10 m. of limestones were seen to separate the quartzites from the Planetfjella schists. Both the position and the thickness of these beds are in doubt.

IIc. The Lower Hecla Hoek

The Planetfjella Series

This series, which has not so far been subdivided, is of a distinctive

semi-pelitic facies. It is usually metamorphosed and shows conspicuous pink feldspar augen set in a dark schistose matrix. The rock weathers pink and can be traced from Nordenskiöldbreen in the south, up the west side of Veteranen in Planetfjella, to the south-west of Gullfaksebreen (where it was recorded by Fleming and Edmonds), and to Sorgfjorden where it is less metamorphosed. Its boundaries are commonly faulted.

The Harkerbreen Series

This is a distinctive series of thick massive-weathering psammites, usually highly deformed and metamorphosed. The series is characterized by amphibolite bands which are very conspicuous in cliff sections, and by means of which structures can be traced from a distance.

In spite of intense deformation, current bedding has been used to confirm the order of succession. The series is conveniently divided into two formations : the Tordenryggen Quartzites above and the Bleikfjellet Psammites below.

The Tordenryggen Quartzites form a relatively uniform series of pink weathering clean quartzites. The thickness is difficult to determine owing to intense deformation, but at least 1,000 m. and possibly more than 2,000 m. may be present.

The Bleikfjellet Psammites are less uniform than the rocks above, being on the whole darker and with alternations of gneiss and schist. They appear to be more resistant to weathering, and form some of the highest mountains with fine cliffs. The top is distinguished by 100 m. or more of multicoloured quartzites with delicate shades of pinks and greens. The lower part contains the very distinctive belt of *Camryggen Gneisses* making up a proportion varying from one-third to two-thirds of the total thickness of the Bleikfjellet Psammites, which are at least 2,000 m. and may exceed 3,000 m. in total thickness. The gneiss belt which appears to be continuous with that first recorded by Blomstrand presents a structural and petrogenetic problem to be considered elsewhere : if it be a metasomatic rock, the whole belt should remain a constituent part of the Bleikfjellet Psammites.

The Finnlandveggen Series

In contrast with the psammitic series above, the upper part of the Finnlandveggen Series is essentially pelitic, and contains conspicuous marble bands. As with the overlying series however, amphibolitic bands are abundant throughout, though except in the group of pink gneisses they are less conspicuous. The pink gneisses are developed in the lowest part of the succession, but they are essentially conformable, and are closely associated with the pelitic series. The whole is grouped together as one series which is involved in complex

deformational structures, so that the equivalence of similar rocks is difficult to determine at this stage.

The Smutsbreen Schists include the whole of the pelitic series. In the east the *Störmerfjellet Schists* represent the main development and comprise about 1,000 m. of pelitic and semi-pelitic schists. Within the schists there are developed conspicuous bands of marble, notably the *Westbyfjellet Marble* and the *Einsteinfjellet Marble* which may prove to be equivalent. The *Lemströmfjellet Schists* are developed in the west and are almost certainly the equivalent of part of the Störmerfjellet Schists, although they lack the very conspicuous carbonate bands in the south.

The Eskolabreen Gneisses (possibly 1,000 m.) includes a whole series of gneisses some of which may be equivalent due to recumbent folding. Two main groups are the *Sederholmfjellet Gneisses* above and the *Lemströmfjellet Gneisses* below. The *Einsteinfjellet Gneisses* may be a third member or the equivalent of one of the above.

The Austfjorden Series

Although the details of the Finnlandveggen Series are likely to be revised, there is little doubt of the general validity of the above succession. However, the westernmost rocks of Ny Friesland have not yet been related because of their tectonic complexity and the lack of good cliff exposures. Grouped together in the Austfjorden Series are a variety of rocks occupying a complex structural belt. On the east of Austfjorden the rocks are largely gneisses and amphibolites, with larger proportions of the latter than in any of the series mentioned above, and there are also schists and subordinate quartzites. To the south-west of Austfjorden there is a strip of dark gneisses, sufficiently uniform and separate from the foregoing to be grouped as the *Cambridgebreen Gneisses.* They are taken as part of the Austfjorden Series.

The Sørbreen Series

West of the Austfjorden Series and exposed along the east coast of Wijdefjorden is a very distinctive quartzite series. This could well be the equivalent of the Harkerbreen Series, but a separate name is used until some correlation can be established. These rocks were examined by Blomstrand, and have long been accessible to coastal parties in the north. Sørbreen reaches Wijdefjorden about 79° 30′ N.

III. Comparison with Published Sections in Svalbard

A. *Central Vestspitsbergen and southern Ny Friesland*

In Central Vestspitsbergen the earliest systematic account of the older rocks is by Tyrrell (1922). Although his is mainly a petro-

graphical account of morainic specimens from the pre-Devonian " basement complex ", Tyrrell gives a section north of Nordenskiöldbreen (p. 216), and our equivalents to his letters are approximately thus : (a) and ? (b) Planetfjella Schists ; ? (b) and (c) Harkerbreen Series ; (d) to (h) Smutsbreen Schists with a marble (e). The exposures mentioned to the east in Horbyebreen are the Camryggen Gneisses. The quartzites to the south-east in Gipsdalen are probably Veteranen Quartzites.

Odell extended this study north-eastwards into southern Ny Friesland, and his results have been correlated by Kulling (1934) and by Fleming and Edmonds (1941). We agree in general with these correlations and the following table of Odell's (1927) succession gives our more detailed equivalents :

Upper Series

No. 7.—The " Cherty Conglomerate " is almost certainly the same as the Draken Conglomerates which are well exposed in Raudberget (Chydeniusbreen), and in Jøkulhøgdene and Ellevepiggane (Oxfordbreen).

No. 6.—The " black and white chert horizon " is probably part of the Draken Conglomerates, the only alternative being a horizon of white non-conglomeratic, chert banded dolomite 30–100 m. thick in the Svanbergfjellet beds, and about 300 m. below the base of the Draken Conglomerates.

No. 5.—The " pale and dark limestones and dolomites of great thickness " suggest the Svanbergfjellet beds and the Grusdievbreen Limestones. In Ellevepiggane the former are thought to be repeated by strike faulting, which would account for the apparent excessive thickness in this area.

No. 4.—The " red shales with thin quartzites and quartzose slates " outcropping on Raudryggen (Chydeniusbreen) may belong to the Fulmarberget Shales.

Lower Series

No. 3.—The " dark dolomitic limestones " have an anomalous position, and we agree with Fleming and Edmonds in referring them to the base of the calcareous series—i.e. our Grusdievbreen Series.

No. 2.—The " dark laminated shales " etc. are probably the equivalent of the combined Enpiggen Beds and the Glasgowbreen Greywackes.

No. 1.—The " purple pink and yellow massive quartzites " are almost certainly the Glasgowbreen Quartzite, which outcrops conspicuously in both Veteranen and Poincaré toppen. They may alternatively belong to the Veteranen Quartzites, but these are dark coloured and the intervening beds are not described. The quartzites are of Flora type.

Thus only a part of the complete Ny Friesland succession is represented in Odell's section. The thickness of his succession according to our equivalents would be about 2,650 m. out of a possible 9,000 m. On the other hand, Odell's overall estimate of 10,000 to 12,000 m. is based on average dips, and width of outcrops including snow-gaps, but

excluding discontinuities such as strike faulting. Our conclusions are thus very similar.

IIIB. *North Ny Friesland and Nordaustlandet*

Nordenskiöld's (1863) original description of this region gives the broad outlines of rock distribution, and consolidates Horner's (1860) description of Parry's collection throughout a similar region. His map still stands in a general way if the following equivalents be applied.

(5) to (7) are later rocks.

(2) " Dolomite " and (4) " Ryssökalk " are Upper Middle Hecla Hoek with small amounts of Upper Hecla Hoek not distinguished.

(3) " Hecla-Hook Formation " is Lower Middle Hecla Hoek.

(1) " Granite Gneiss " is Archaean in the east and Lower Hecla Hoek in the west.

Bloomstrand's map (1864) distinguishes the succession west of Sorgfjorden, and his alternating " Quartzite " and " Amphibolite " largely comprise the Sørbreen Series. His " Granit " is the analogue of the Camryggen Gneiss, and his " Glimmerskiffer " is broadly equivalent to the Planetfjella Series. His belt of " Quartzite " just west of Sorgfjorden probably belongs to the Lower Veteranen Series.

The classic Heclahuken section was again visited by Kulling who consolidated Nordenskiöld's and Blomstrand's work. We confirm Kulling's observations and also recognize our own southern succession. There is a single large overturned anticline plunging to the south-south-east with the lowest beds east of the summit ridge of Heclahuken. Kulling's recognition of Hunnberg Limestones (K. 1–3) on the eastern shore of Sorgfjorden is almost certainly correct. The calcareous rocks (K.12–14) to the east, however, probably correspond to the Cavendishryggen Limestones, as they are of similar facies and underlie thick Glasgowbreen and Cavendishryggen Quartzites (K.6–11) which form the summit ridge of Heclahuken. The rocks forming the eastern flank of Heclahuken (N.8) are in fact dark, thick-bedded quartzites of uncertain horizon, which young to the east.

Kulling's outstanding contribution to Hecla Hoek stratigraphy was his definitive account of the succession in Nordaustlandet (1932 and 1934). The following summarizes our correlations, which are broadly set out in Table II.

Kap Sparre Formation

The fossiliferous *Upper Dolomite* is thought to be Lower Cambrian, and therefore probably corresponds with the Oslobreen Dolomites. However, the *Lower Dolomite Series* is underlain by the *Lower Quartzite* and *Lower Shale Series* which correlate well with the Oslobreen Sandstone and the Upper Polarisbreen Shales. It is not impossible that the Upper and Lower Series are the same duplicated by faulting, for the succession was evidently

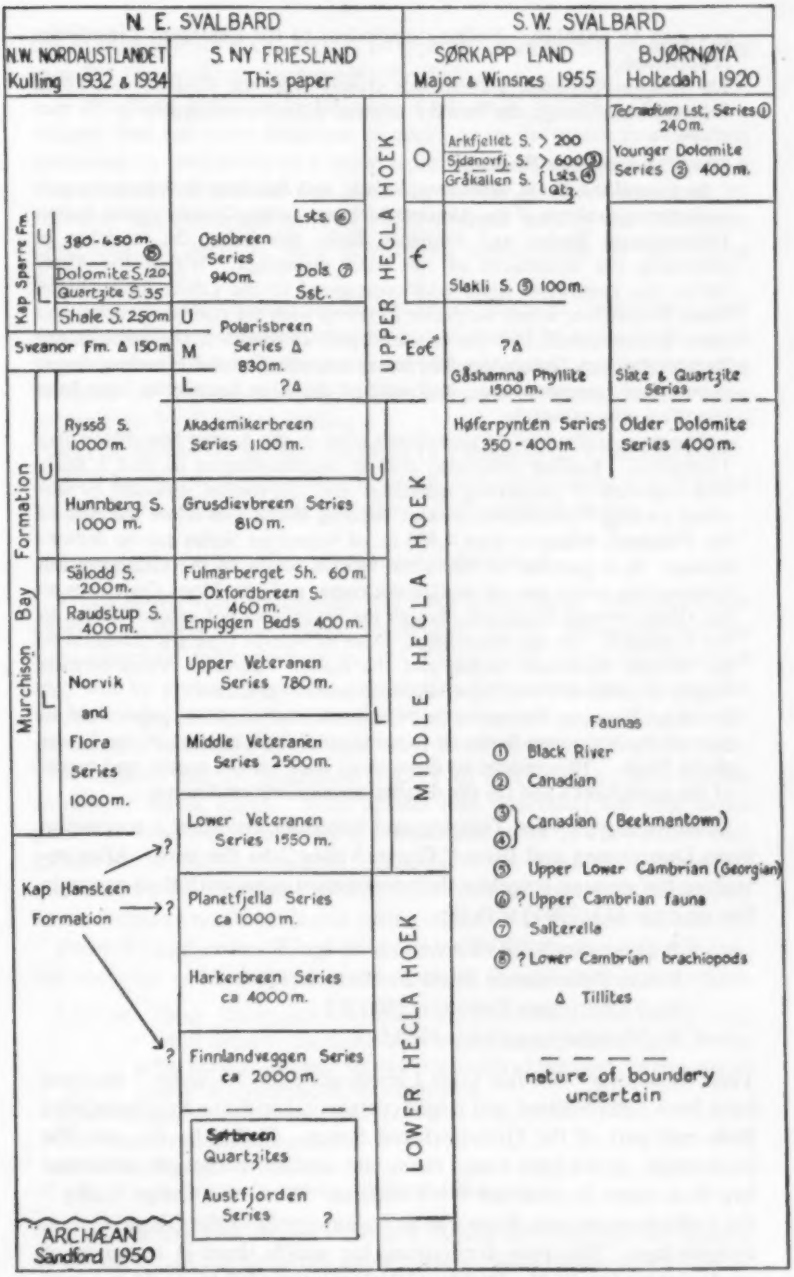


TABLE II.—Correlation of Hecla Hoek rocks in Svalbard.

not easy to establish. Nothing equivalent to the Oslobreen Limestones is apparent.

The Sveanor Formation corresponds closely with the Polarisbreen Tillite Formation, although the boulder content differs considerably in the two areas.

The Murchison Bay Formation

In general the *Ryssö, Hunnberg, Sälodd,* and *Raudstup Series* are respectively the equivalents of the Akademikerbreen Series, Grusdievbreen Series, Fulmarberget Shales, and Enpiggen Beds, this being the intention in proposing the boundaries of the latter groupings. Within the *Ryssö Series,* the uppermost shaly beds correspond to the Lower Polarisbreen Shale Formation, which we prefer to group with the overlying rocks, and there is little doubt that the typical Ryssö Dolomite is the same as the Backlundtoppen Dolomite. The lower boundary of the *Hunnberg Series* shows clear correspondence, and most of the other boundaries have been identified approximately.

The main difficulties of correlation arise in the Lower Murchison Bay Formation. Kulling concluded that in Nordaustlandet he had a fairly thin sequence of alternating quartzites and greywackes repeated by isoclinal folding. Ubiquitous current bedding shows this is not the case in Ny Friesland, where at least 4,500 m. of Veteranen Series can be demonstrated. It is possible to relate the Norvik Series to the Glasgowbreen Greywackes which are of similar thickness, and the Flora Quartzites to the Glasgowbreen Quartzite, though the latter does not exceed 400 m. in Ny Friesland. On the other hand, rocks of Norvik type are abundant in the Middle Veteranen Series, and the Lower Veteranen Series consists largely of rocks of Flora Type, although somewhat darker.

The Kap Hansteen Formation in Nordaustlandet might be equivalent to part of the Veteranen Series or to some amphibolitic series of the Lower Hecla Hoek. This cannot be determined until (a) the nature and extent of the pyroclastics and (b) the detailed successions are known.

South of Sorgfjorden Fleming and Edmonds recorded a succession from Dunérbreen and from " Gorge Valley " to the east. After revisiting the area we correlate their succession given with thicknesses in feet on page 413 (1941) with the

Polarisbreen Tillite Formation
Lower Polarisbreen Shale Formation (570 ft.)
Backlundtoppen Dolomite (500 ft.)
and Backlundtoppen Oolite (850 ft.)

Their remaining " 450 feet Grey Limestones and Dolomites " may not have been differentiated and might correspond with the Svanbergfjellet Beds and part of the Grusdievbreen Series. If this be the case the thicknesses, as we have found them, are similar to though somewhat less than those in southern Ny Friesland. West of " Gorge Valley " the rocks seem to pass down almost continuously to the Glasgowbreen Greywackes. The only formations for which there is evidence of marked thinning are the Draken Conglomerates (300 m. to 24 m.), and

the Svanbergfjellet Beds (300 m. to around 120 m.). No evidence was seen for an unconformity beneath the Tillite.

Intermittent outcrops to the west, such as in Sørfjellet (Syd Mts.), suggest that the same thickness of rocks as in the south passes down continuously westwards to a rapid transition to Planetfjella Schists on Rosenfjellet. If this be the case, the Sørfjellet rocks described by Fleming and Edmonds represent only a small part of the Veteranen Quartzites, in spite of their lithological resemblance to the Upper Veteranen Series.

A good lithological correlation can be made across Dunérbreen, and it seems that the Sørfjellet sequence is transferred by a dip fault across Dunérbreen to Rosenfjellet in the north-west. Here, as elsewhere, the evidence of current bedding precludes any interpretation of these successions by isoclinal folding.

In Faksebreen the section recorded by Fleming and Edmonds (1941, p. 423) has not been correlated in detail, but some of the gneisses and schists as described suggest that they are Planetfjella Series.

IIIc. *Western Spitsbergen*

From north-west Spitsbergen we have accounts of reconnaissance expeditions early in the century (Holtedahl 1926). No succession has been described and the whole variety of rock types met in Ny Friesland may well be present, including concordant granite gneisses. It may be worth noting that limestones and dolomites are recorded and are particularly abundant in the basal Old Red Sandstone conglomerates. This suggests that the succession reaches up well into the upper Middle or Upper Hecla Hoek. Mica Schists and quartzites are now more generally exposed, suggesting a predominance of lower Middle and Lower Hecla Hoek equivalents. This is also the case in most of central and western Ny Friesland to-day. Holtedahl interprets the increasing metamorphism northwards as a deeper exposure of the same succession.

From Kongsfjorden (Kings Bay) Orvin (1934) gave the only substantial sequence of Hecla Hoek rocks recorded from western Spitsbergen.

1,600 m. *Upper Limestones* (metamorphosed) overlie a thick quartz mica schist series to the north of Kongsfjorden. Assuming this to be the same as a similar series to the south of the fjord the succession may be continued downwards thus :

2,500 m. *Quartz Mica Schist Series.*

270 m. *Steenfjell Dolomites.*

1,500 m. *Begegg Mica Schist.*

? *Dolomitic Limestones* of Forelandsundet.

Comparing this with the Ny Friesland Succession, the thick carbonates at the top could belong to the upper Middle Hecla Hoek, which is what Orvin suggests by analogy with Bjørnøya (Older Dolomites). The

remainder may then be equivalent either to the lower Middle or the Lower Hecla Hoek, though in either case the rocks are more pelitic than in Ny Friesland ; and this, together with the occurrence of thick carbonates, suggests a development further from the main source of sediment. The absence of amphibolites may also be explained by distance from a pyroclastic source, but it is simpler to assume correspondence with lower Middle Hecla Hoek and thus equate the whole continuous succession of about 6,000 m. with the Middle Hecla Hoek of Ny Friesland, which is there at least 7,000 m.

Boulder beds resembling tillites have long been known from two localities in western Spitsbergen, Bellsund (Garwood and Gregory 1898), and St. Jonsfjorden (Holtedahl 1913). More recently another such bed has been found North of Hornsund, and this Major and Winsnes (vid. inf.) place between their Slakli and Høferpynten Series, a horizon closely analogous to that of the north-east Svalbard tillites. Although the western Spitsbergen boulder beds differ considerably from one another, the variety within the known north-east Svalbard tillites is sufficient to allow for this, and it is reasonable to suppose that all these beds represent the (? unique) Eo-Cambrian tillite. If we assume this, it follows that in mid-western Spitsbergen both Upper and Middle Hecla Hoek are present. This is consistent with both the proved Upper Hecla Hoek to the South and the assumed Middle Hecla Hoek further North.

Little is yet published of the stratigraphy of the Hecla Hoek of Prins Karls Forland, though field work has been completed recently ; but in the meantime we have some idea of the nature of the rocks from Tyrrell's description, from which it seems that the main lithological varieties may be matched in many parts of our succession. If the epidiorites represent part of the original succession this suggests correlation with the Lower Hecla Hoek, but it seems more likely that they are later intrusives and therefore of no assistance in stratigraphy.

From Sørkapp Land in the extreme South of the mainland, Major and Winsnes (1955) have given a well dated succession which is somewhat disconnected by faulting and ice cover.

Canadian cephalopod faunas have been described from the top division of the *Sjdanovfjellet Series*, and other Lower Ordovician fossils have come from the *Gråkallen Limestones*. The *Tsjebysjovfjellet Series*, which is probably equivalent in parts to the Gråkallen Limestones, contains similar Lower Ordovician fossils. In none of these series is there evidence of other than Ordovician age. The rocks are mainly calcareous and the total thickness may be of the order of 1,700 m. None of these rocks has yet been matched in north-east Svalbard, but there is a close parallel with the Upper Dolomite Series of Bjørnøya in age and lithology but not in fauna.

The *Slakli Series* of which only 100 m. is exposed, is subdivided into black shale (top), pale quartzite, and sandy limestone. The last contains

an *Olenellus* fauna, and may well parallel in age the Kap Sparre and Lower Oslobreen Series.

At an uncertain interval below the Slakli Series there is thought to be a boulder or tillite horizon, overlying 1,500 m. of *Gåshamna Phyllites* which are analogous to the Lower Polarisbreen Shales. Discontinuously beneath these are the dolomites of the *Høferpynten Series* which are not unlike those of the Akademikerbreen Series.

IIID. *Bjørnøya*

Bear Island long provided the only fossiliferous Hecla Hoek succession for international comparison (Holtedahl 1920).

The *Tetradium Limestone* (240 m.) is of Black River age—higher than anything proved elsewhere in Svalbard.

The *Younger Dolomite Series* (400 m.) has a Canadian fauna.

The *Slate-Quartzite Series* (175 m.) has not yielded fossils. It could be Cambrian but is most likely equivalent to the Gåshamna Phyllites or Polarisbreen Series.

The *Older Dolomite Series* (400 m. oolitic and stromatolitic) compare well with the Akademikerbreen Series.

IV. Conclusions

An apparently continuous and bottomless succession of Hecla Hoek rocks has been described from Ny Friesland. The rocks range down from at least the Upper Cambrian and total not less than 16,000 m. (say 50,000 feet). Such a thickness throughout Ny Friesland implies a considerable geosyncline. Throughout the succession, in both carbonate and quartzose facies, there is evidence of relatively shallow water sedimentation, and in the lower part of rapid deposition.

The Lower Hecla Hoek (ca. 7,000 m.) consists primarily of psammitic and semipelitic rocks with abundant evidence of contemporary igneous activity, and it therefore represents a distinctive eu-geosynclinal phase. The Middle Hecla Hoek contains a further 5,000 m. of quartzose sediments, but in the suceeding 2,000 m. its character changes abruptly to a carbonate facies. The Upper Hecla Hoek consists of shales with tillites (ca. 800 m.) and is followed by 1,000 m. of Cambrian limestones. The Middle and Upper Hecla Hoek together represent a mio-geosynclinal phase with an apparently reduced rate of deposition in the top 4,000 m.

The shape of the original geosyncline is obscured by folding about north-south axes, but the constancy of thickness and facies suggests that it extended beyond the limits of the present peninsula, although there is evidence that the eastern margin of the eu-geosyncline is marked by a change of tectonic facies. To the north-east, in Nordaustlandet, a distinct Archaean foreland appears beneath Hecla Hoek sediments, where they apparently total less than 5,000 m. This is at a distance of little more than 20 km. from Ny Friesland, and the great

difference in thickness arises almost entirely in the lower Middle and Lower Hecla Hoek.

The Ordovician carbonate rocks in south-western Svalbard may total 1,700 m. in Sørkapp Land and 640 m. in Bjørnøya. Of the remainder of the sequence only a small thickness may be correlated with the succession in north-east Svalbard.

Elsewhere in western Spitsbergen there are no adequate published successions or thicknesses with which to make comparisons; however, the presence of boulder beds, and the suggested correlation of most of the dolomites with the Middle Hecla Hoek suggests that many of these rocks are Pre-Cambrian, which would explain the lack of fossils discussed by Holtedahl (1920). It is not impossible that similar successions will soon be worked out in this area where there is an encouraging similarity of facies.

If it be assumed, as seems reasonable, that most of the Eo-Cambrian tillites throughout the World represent one major ice age then we have the basis of a very satisfactory datum for correlation. The observations recorded in this paper add to the cases where a marine (or at least an aqueous) tillite is followed apparently conformably by marine Lower Cambrian beds and preceded by a conformable series of limestones barren, except for algal remains, yet with lithology suitable for the preservation of fossils. We must envisage widespread refrigeration probably accompanied by fall of sea-level and worldwide peneplanation. This would be followed by a general climatic amelioration accompanied by a general transgression which together may partly account for the arrival of Lower Cambrian faunas both in transgressive deposits and in continuous marine successions

Wider correlations other than of the Eo-Cambrian Tillite are bound to be speculative in the absence of palaeontological or other control. However, without implying correlation, there is a marked similarity in the Caledonian geosynclinal sequence over wide areas, not only in the shelf regions of Cambrian transgressions, but even in the axial regions of thick late Pre-Cambrian deposition. The comparison with Scandinavia and Greenland is summarized by Katz (1953). Kulling (1932) first showed in detail the similarity between the Hecla Hoek and Greenlandian successions by correlating his Murchison Bay Formation with the Eleonore Bay Formation, his Sveanor Formations with the Kap Oswald Formation, and the Kap Sparre Formation possibly with the Lower Cambrian of Greenland. The latest account of the Greenlandian rocks and their structural relations (Haller 1955) increases the similar appearance of the two areas to a remarkable degree. Similar analogies with the Dalradian have often been applied. As far away as the Appalachians the traditional problem of the status of metamorphosed piedmont rocks bordering a belt of open fold mountains in the

Blue Ridge Province has recently been examined by Bloomer and Werner (1955), who demonstrated the continuity of late Pre-Cambrian and Lower Palaeozoic sedimentation into the metamorphic belt.

V. Acknowledgments

To avoid frequent parentheses, our separate responsibilities for observations and opinions in this paper have not been distinguished. Broadly, one of us (W. B. H.) has supervised all the structural work and the stratigraphy of the Lower Hecla Hoek, and the other (C. B. W.) has made a special study of the petrology and stratigraphy of the Middle and Upper Hecla Hoek.

Structural and petrological details have been omitted from this account for reasons of space, but the stratigraphy is intimately dependent on them, and in turn on the geological and topographical survey of this little known region. It will also be left to other papers to outline the parts played by successive expeditions in 1949, 1951, 1952, 1953, 1954, and 1955 and their many members. In particular we wish to thank Mr. Masson-Smith who accompanied four of these and provided a rigorous triangulation control for all the surveys. In connection with the Hecla Hoek studies we are most indebted to Mr. M. B. Bayly who during three of his five visits was engaged on the detailed petrology and structure of the Lower Hecla Hoek. Dr. R. H. McWhae, the late Dr. P. F. Hutchins, Dr. M. H. P. Bott and Dr. W. Schwarzacher also made substantial contributions.

The expeditions depended on help from many quarters, principally the Royal Society for financial support, and the Royal Navy for transport on two occasions. The Norwegian authorities in the Norsk-polarinstitutt, Oslo, and in Longyearbyen in Svalbard have given us every help, and we are particularly indebted to Dr. A. K. Orvin and Governor Balstad. Dr. H. Major kindly corrected some inaccuracies in the manuscript.

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Petrology of the Anorthosite-Gabbro Mass at Kadavur, Madras, India[1]

By A. P. SUBRAMANIAM

(PLATE X)

ABSTRACT

A small body of anorthosite with related gabbroic facies from the Archaean of Southern India is described. The mass is inferred to be a funnel shaped phacolithic pluton, emplaced in the crest of a steeply plunging major anticline of metasedimentary quartzite and quartz schists. The marginal rocks of the mass are gabbroic and foliated, while the core is largely made of massive anorthosites occasionally showing flow structures. The chemistry and petrography of the rocks of this mass suggest their having resulted from differentiation in place of a gabbroic anorthosite intrusion. This occurrence is thought to be a unique example of the Adirondack type of anorthosite, and supports Buddington's hypothesis of evolution of anorthositic rocks from a gabbroic anorthosite magma.

INTRODUCTION

THE writer's attention was drawn to these rocks by his colleague Mr. S. Narayanaswami, of the Geological Survey of India. Preliminary petrographic examination of some specimens by the writer revealed them to be anorthositic rocks of the Adirondack type. As such rocks had not been recorded in Southern India, the writer was kindly permitted by the Director, Geological Survey of India, to make a field study of the area; and later carry out detailed petrographic examination.

LOCATION

This mass of anorthosite-gabbro occurs in the Kadavur area in Tiruchirapalli district, Madras, India, between latitudes 10° 32′ and 10° 37′ and longitudes 78° 9′ and 78° 15′ represented on Survey of India Topo-Sheet 58 J/2. These rocks occupy an area of about 20 square miles and are found within a structural basin surrounded by an almost circular ridge of quartzites and related metasediments. The area is about 14 miles WNW of Vaiyampatti Railway Station in the Madras–Madura main line of the Southern Railway.

GEOLOGICAL SETTING

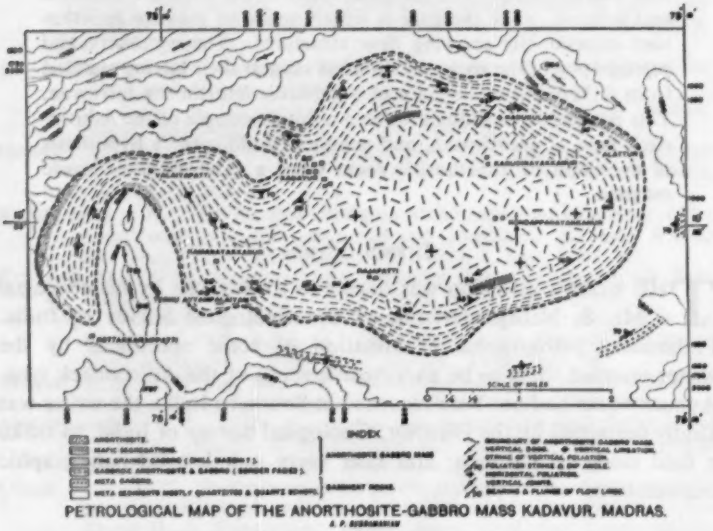
The petrology and structure of the anorthosite-gabbro mass and

[1] Published by permission of Director, Geological Survey of India.

adjacent area are shown in Text-fig. 1. The sequence of rocks types in the area is as below:

Recent	Soil cover and kankar
Archaean	Quartz veins and pegmatites
	Anorthosite-gabbro mass with included mafic layers.
	Quartzite, quartz schist, pyroxene granulite, metagabbro, amphibolite, calc-granulite, and crystalline limestone.

The metasedimentary rocks comprising quartzites and quartz schists



PETROLOGICAL MAP OF THE ANORTHOSITE-GABBRO MASS KADAVUR, MADRAS.

TEXT-FIGURE 1.

form a group of ridges which encircle a basin occupied by anorthosites and gabbros. Thin layers and bands of pyroxene granulite and metagabbro, representing older basic sills or sheets, are found among these quartzites and quartz schists. Other rock types in the metasedimentary group are amphibolites, calc-granulites and crystalline limestone. The anorthosite-gabbro mass is roughly 6 miles in length and attains a maximum width of about three miles.

STRUCTURE

The circular quartzite ridges just referred to form a major structural feature, brought out clearly in topographic maps. The rocks, mostly

quartzites and quartz schists, have almost vertical bedding. At some points these beds show a distinct down dip lineation, which is a grooving caused by slipping of beds during deformation. This lineation may indicate the axis of the fold structure standing on edge or plunging very steeply. On this assumption, these circular groups of quartzite ridges are interpreted as the limbs of a large anticlinal structure plunging almost vertically to the west. Another possible interpretation would be that these quartzite ridges form the outer rim of a synclinal depression with an indefinite trend. In view of the general complexity of structures in the Archaean terrain, and in the absence of a regional picture of the structure of the area, it appears reasonable to adopt the first interpretation.

The anorthosites and related gabbroic rocks occupy the centre of the basin or structurally the crest of the major fold structure. The rocks in the peripheral zone are well foliated and gabbroidal gradually becoming anorthositic towards the centre of the mass. Chatterjee (1936, p. 22) records foliated mafic types along the margins of the Bengal anorthosites which are generally massive and devoid of foliation. Such gabbroidal marginal rocks have also been recorded in the Adirondack anorthosites by Buddington (1939), and in the anorthosites of Laramie Mountains by Fowler (1930). These mafic anorthosites and gabbros in the peripheral zone have inward dips of foliation varying from verticality to about 30° when approaching the massive anorthosite core. The passage from gabbroic rocks to mottled anorthosite and finally coarse anorthosite is observed in several small stream sections across the foliation. The inward dipping foliation noticed in the peripheral zone becomes almost horizontal towards the centre. Platy flow structure, trending ENE.-WSW. and plunging 30–50° SW. is noticed in the coarse anorthosites south and east of Rajapatti which have a gentle inward dip of foliation. The south-westerly plunge of the flow lines perhaps indicates a possible tilting of the intrusive body after emplacement. Two systems of vertical joints are noticed in these rocks, one set striking N.–S. and another NE.–SW. The small streams south of Kadavur follow these joint directions.

The structural data gathered from the various exposures of these rocks, suggest the mass to be a funnel shaped pluton emplaced within the crest of a steeply plunging regional anticline during a period of quiescence. The peripheral foliation of the rocks and their concentric dips towards the core of massive structureless anorthosite, suggest a synclinal form for the entire mass. According to Balk (1937, pp. 93–94) such funnel like or similar synclinal forms characterize many gabbro masses. The Kadavur mass shows some similarity to the gabbro phacoliths of the Sulitelma region described by Vogt (1927).

Rock Exposures

Good exposures of these anorthosite-gabbro series of rocks are seen at the following points in the Kadavur basin :—
(1) Near Sirumampatti, half a mile east of Kadavur, (2) one mile north east of Kadavur in the small water courses, (3) at Kadavur in the temple garden area, (4) about two miles east of Kadavur, along northern margin of Vaiyampatti road, (5) two furlongs east of Nadukulam, (6) around Karudinayakkanur, (7) around Kondappanayakkanur (loose boulders of ilmenite are found in this area), (8) north of Idaiyapatti, (9) near Rajapatti and in the stream section nearby, (10) in the various stream and water courses north east of Kadavur.

Petrology

As mentioned earlier the rocks in the Kadavur mass vary in mineralogical composition from a feldspathic gabbro to anorthosite, the various passage types being encountered in the field. The transition can be indicated as below:

Feldspathic gabbro → blotchy gabbro → mottled anorthosite → anorthosite.

The fine-grained gabbros noticed along the margin of the mass near Valaiyapatti and Alattur may represent chilled marginal gabbros. The marginal rocks are well foliated and grade to dioritic types near contacts with the metasediments. The anorthosites in the margins are fine-grained and granulated, but towards the core of the mass they show pronounced increase in grain size of individual minerals, particularly the feldspars. The feldspars in the massive anorthosites of the core vary in length from half an inch to four inches or more and appear to be set in a matrix of granular feldspar, presumably resulting from protoclastic granulation. In one or two outcrops of coarse anorthosites, the feldspar crystals show a preferred orientation, which must be attributed to magmatic flowage. Within the anorthosites, mafic layers and lenses rich in ores are also seen. Such layers have been noticed in the Adirondack anorthosites and gabbroic anorthosites by Buddington (1939, p. 34). Taking the mass as a whole anorthosites predominate over gabbroic types. The different rock types in this anorthosite gabbro mass have been recognized following Buddington (1939, p. 19), and the rocks genetically related are: anorthosites, gabbroic and noritic anorthosites, anorthositic gabbro, and minor layers of ilmenite-magnetite pyroxenite.

Mineralogy

The minerals found in these rocks in order of abundance are : plagioclase feldspar (An_{35}–An_{60}), green hornblende, orthopyroxene

(En_{45}–En_{80}), clinopyroxene, and minor amounts of scapolite, calcite, apatite, sphene, ores and biotite.

Plagioclase feldspar. The plagioclase feldspar in these rocks was found to have a uniform composition of An_{50-55}, with some of the marginal types having An_{38} and some of the core anorthosites having An_{60}. The compositions which were determined by measuring α on cleavage fragments, have been read from the curve presented by Poldervaart (1950, p. 1065). These values ranged from 1·546 to 1·561, but generally in most rocks they were found to be 1·555 ± ·002. Determination of extinction angles in thin sections also gave similar values for the composition of these feldspars, which can be considered to be labradorites. Generally they are pearly or greyish blue in colour, but some of the anorthosites in the core contain dark pinkish grey feldspars. In thin section these coloured feldspars were found to have a pronounced schiller structure, caused by arrangement of liquid and gas inclusions, and dark rods and plates of ores. They are generally twinned, but the granulated margins around some of the larger plates carry a few untwinned grains. Twinning of the albite, pericline and albite-Carlsbad types are quite common, while many plates display both albite and pericline twinning. Some of the marginal gabbroic types show bent twin lamellae, which must be attributed to movement during emplacement and cooling of the mass. The granulated margin around the larger plates of feldspar of the core anorthosites is sometimes observable even in hand specimens as thin rims. Such marginal granulation of plagioclases of anorthosites has been recorded by Chatterjee (1936, p. 21) in the Bengal anorthosites, and Fowler (1930, p. 375) in the anorthosites of Laramie Mountains. Fowler has attributed the granulation to protoclastic deformation, and as stated earlier the granular margins of the larger plates of feldspars of the Kadavur anorthosites may well have been caused by movement of unconsolidated magma. Alteration to scapolite and calcite along the cleavages is noticed in some of the larger plates of feldspar.

Hornblende. Hornblende is the common mafic mineral of the rocks of the mass being more abundant in the peripheral gabbroic rocks. It appears to have been derived from the primary pyroxenes, by action of late stage mineralizers. In some thin sections the hornblende aggregates carry a core of primary pyroxene. Generally hornblende occurs as spongy aggregates, retaining the crystal outline of the primary pyroxene. Some of the larger grains show an intensely pleochroic margin, which may indicate a slight difference in composition from the core. The following optical properties are shown by these hornblendes, which indicate them to be calciferous amphiboles according to Winchell (1945).

$\alpha = 1{\cdot}638 - 1{\cdot}648 \pm 005$ X = pale yellowish green
$\beta = 1{\cdot}648 - 1{\cdot}658 \pm 005$ Y = pale bluish green
$\gamma = 1{\cdot}668 - 1{\cdot}678 \pm 005$ Z = dark bluish green
$\gamma \wedge c$ 16 – 18° ± 2, (–) 2V = 80° ± 3°, X < Y < Z

Pyroxenes. Both ortho and clinopyroxenes are seen in these rocks. The orthopyroxenes were found to have a compositional range En_{80} to En_{55} as indicated by values of γ ranging from 1·690 to 1·720. The orthopyroxene in the ilmenite pyroxenite was found to have $\alpha = 1{\cdot}738$, indicating a composition of En_{42}. The compositions of these orthopyroxenes have been read from the curves of Hess (1952), and indicate them to vary from bronzite to ferrohypersthene, according to the classification adopted by Poldervaart and Hess (1951). These orthopyroxenes are pleochroic in pale salmon pink and green, the intensity of the absorption being related to the 'Of' content. They also show well developed lamellar structure of the Bushveld type. Some of the larger plates of hypersthene contain small inclusions which are pleochroic in browns and rectangular in outline. They are arranged parallel to the base and sometimes at an angle to the c axis. They may be titaniferous mica or microplakite described by Johannsen (1939, p. 235).

Most of the clinopyroxenes in the anorthosites have been altered to amphibole, but in the ilmenite-magnetite pyroxenites they are fresh and have the following optical characters showing them to be ferroaugites:—

$\alpha = 1{\cdot}688 \pm 005$
$\beta = 1{\cdot}694 \pm 005$ 2V = + 60° ± 2
$\gamma = 1{\cdot}714 \pm 005$ $\gamma \wedge c$ = 41° ± 2

Scapolite and *calcite* occur in most rocks, invariably due to alteration of the subcalcic plagioclase. Occasionally *apatite*, *sphene*, *biotite* and *ores* are seen in these rocks.

Petrography

The anorthosites in general are coarse grained and bluish or pinkish grey in colour. With increase in the proportion of mafic minerals, the rocks get mottled with greenish blotches of hornblende and occasional brown coloured grains of orthopyroxene. In more mafic types there is a reduction in the grain size of the various minerals. The gabbroic anorthosites and feldspathic gabbros display typical gabbroidal texture. The density of these rocks ranges from 2·72 to 3·0. Petrographic descriptions of the analysed specimens and a few others follow:

*Anorthosite K.*29. The rock is greyish blue in colour and medium to coarse grained with the plagioclase plates varying from quarter of an inch to two inches in length. In thin sections the rock is made up

essentially of plagioclase An_{52} ($\alpha = 1{\cdot}555$), granular aggregates of hornblende and a few grains of orthopyroxene En_{66} ($\gamma = 1{\cdot}690$). The feldspars carry abundant oriented inclusions, are generally turbid, and the large plates have granulated margins (Pl. X, fig. 1). A few grains of apatite, ores, calcite and scapolite are often present. The orthopyroxene grains show peripheral alteration to hornblende, and much of the hornblende present in the rock appears to have been derived by paramorphic alteration of pyroxenes.

*Noritic anorthosite K.*10. This is a massive coarse grained dark variety of anorthosite, composed largely of pinkish grey plagioclase feldspar plates ranging from half to three inches in length. Thin sections are found to be composed of plagioclase An_{58} ($\alpha = 1{\cdot}558$), orthopyroxene En_{76} ($\alpha = 1{\cdot}694$), and a few grains of hornblende, scapolite and calcite. The feldspars have a turbid appearance, and carry oriented rod shaped inclusions, which may be the cause of their colour. Peripheral granulation attributable to protoclastic deformation is exhibited by many of the larger plates of feldspar. In one thin section, a large plate of orthopyroxene was found to carry several insets of labradorite. (Pl. X, fig. 2). The orthopyroxenes show peripheral alteration to green hornblende. Scapolite, ores, biotite and calcite occur in minor amounts.

*Gabbroic Anorthosite K.*23. The rock is medium grained with a blotchy appearance due to the clustering of granular aggregates of hornblende in a matrix of plagioclase. The feldspars have a pinkish grey colour, and some of the larger crystals display a granular rim. In thin section the feldspars are turbid and carry oriented rod shaped inclusions. Some of the larger plates carry inclusions of pyroxene and rare spindles of microcline. Most of the feldspar plates are twinned, but the granular feldspars around the larger plates show several untwinned grains. The composition of the plagioclase is An_{55} ($\alpha = 1{\cdot}556$). Hornblende is the most abundant mafic mineral present and appears to have been largely derived from the pyroxenes. It occurs as granular aggregates and rims around the orthopyroxenes. The orthopyroxene is En_{66} ($\gamma = 1{\cdot}708$), carries the platy inclusions referred to earlier, and also displays well developed lamellar structure. Scapolite, calcite, apatite, sphene and ores occur in minor amounts.

*Anorthositic gabbro K.*32. This type is coarsely foliated and displays a typical gabbroidal texture with crystals of plagioclase up to an inch in length set in a matrix of granulated feldspars and other mafic minerals. The feldspars are found to have a composition of An_{50} ($\alpha = 1{\cdot}554$), and in thin sections show ophitic and subophitic relationship with the pyroxenes (uralitized.) They display protoclastic granulation, and sometimes show bent twin lamellae. The feldspars are turbid due to the presence of dusty inclusions of ores and pyroxenes. The mafic

mineral present is green pleochroic hornblende derived from the primary pyroxenes. A fair amount of ores (ilmenite + magnetite) is found near the aggregates of hornblende, while calcite and scapolite appear to have been derived from the plagioclase. Some apatite and rare grains of sphene are also present.

Ilmenite-magnetite pyroxenite. This type occurs as thin layers and lenses within the anorthosites, and is composed of pyroxenes and ores. Both the clino- and orthopyroxene are iron rich varieties. The orthopyroxene En_{43} ($\gamma = 1{\cdot}738$) shows lamellar structure and also carries platy inclusions of a brown mineral, referred to earlier. The ores appear to be later than the silicates in the paragenetic sequence and are seen filling the interspaces between the pyroxene crystals and even replacing them (Pl. X, fig. 3).

Feldspathic gabbro (*chill margin?*). This type is characterized by its granulitic texture in hand specimens and thin sections (Pl. X, fig. 4), and has the same mineral assemblage as the gabbroic anorthosite described earlier, with a higher proportion of orthopyroxene and ores. The orthopyroxene is hypersthene En_{66}. The clinopyroxene is diopsidic augite and shows paramorphic alteration to green amphibole. The plagioclase is labradorite An_{60-70}. It is turbid and shows alteration to scapolite and calcite.

Metagabbro (*pyroxene garnet granulite*). This type is granulitic and contains a fair proportion of garnet. Thin sections show typical granulitic texture with the feldspars having polygonal outlines. The feldspars are free from turbidity and a large proportion of crystals are untwinned. They vary in composition from An_{35-45}. The rest of the rock is composed of almost equal proportions of garnet, hypersthene and diopside. Sphene, biotite and ores occur in trifling amounts. This type is not related to the anorthosite-gabbro series, and is interpreted as a much older gabbro, metamorphosed and recrystallized. It differs from the chill margin gabbro in containing garnet with occasional symplectite margins, and shows a texture indicative of recrystallization.

Mineralogical and textural variants of the main types described above are found within the anorthosite-gabbro mass, but as stated earlier there is a progressive impoverishment in mafic minerals from the margin to the core. The modal compositions of the analysed rocks and a few others are given in Tables 1 and 2.

Chemistry of the Rocks

In Table 1 the chemical composition of four distinct types of rock from the Kadavur mass together with their normative and modal compositions are shown. The analysed specimens are of types which

TABLE 1.—CHEMICAL, NORMATIVE AND MODAL COMPOSITION OF KADAVUR ANORTHOSITES

	K.29	K.10	K.23	K.32	Average
SiO_2	50·59	51·57	51·39	50·62	51·04
TiO_2	0·19	0·25	0·24	0·33	0·25
Al_2O_3	29·00	25·83	22·20	21·78	24·70
Fe_2O_3	1·17	1·66	1·19	1·37	1·35
Cr_2O_3	Tr	Tr	Tr	Tr	Tr
FeO	0·94	1·63	3·13	3·29	2·25
MnO	0·02	0·04	0·07	0·06	0·05
MgO	1·17	3·18	5·30	5·95	3·90
CaO	12·11	11·86	11·98	12·06	12·00
Na_2O	3·48	3·23	2·94	2·78	3·11
K_2O	0·29	0·33	0·30	0·43	0·34
CO_2	0·49	0·21	0·41	0·37	0·37
P_2O_5	0·06	0·05	0·07	0·05	0·06
H_2O^+	0·75	0·44	0·69	0·55	0·61
H_2O^-	0·11	0·08	0·05	0·13	0·09
Cl	0·05	0·04	0·03	0·04	0·04
Less 'O' for Cl	0·01	0·01	0·01	0·01	0·01
Total	100·41	100·39	99·98	99·80	100·15
S.G.	2·72	2·74	2·87	2·96	2·82

Analyst: A. K. Majumdar, P. D. Malhotra, P. D. Malhotra, A. K. Majumdar.

NORMS					
Quartz	2·76	2·10	1·02	–	1·20
Orthoclase	1·67	1·67	1·67	2·22	1·67
Albite	29·34	27·25	24·63	23·58	26·20
Anorthite	57·27	55·04	46·70	45·87	52·54
Diopside Wo		1·28	4·41	4·99	2·09
Diopside En	–	0·90	3·10	3·60	1·50
Diopside Fs		0·26	0·92	0·92	0·40
Hypersthene En	2·90	7·00	10·20	11·30	8·20
Hypersthene Of	0·26	0·92	3·30	2·77	2·11
Magnetite	1·86	2·32	1·86	2·09	2·09
Ilmenite	0·46	0·46	0·46	0·61	0·46
Calcite	1·10	0·50	0·90	0·80	0·80
H_2O	0·86	0·52	0·74	0·68	0·70
Femics	5·48	13·14	24·25	26·28	16·85
Normative plagioclase	$An_{66}Ab_{34}$	$An_{67}Ab_{33}$	$An_{66}Ab_{34}$	$An_{66}Ab_{34}$	$An_{66}Ab_{34}$
Modal plagioclase	$An_{52}Ab_{48}$	$An_{58}Ab_{42}$	$An_{55}Ab_{45}$	$An_{50}Ab_{50}$	$An_{54}Ab_{46}$
Normative Orthopyroxene	$En_{91}Of_{9}$	$En_{88}Of_{12}$	$En_{75\cdot5}Of_{24\cdot5}$	$En_{80}Of_{20}$	$En_{79}Of_{21}$
Modal Orthopyroxene	$En_{80}Of_{20}$	$En_{76}Of_{24}$	$En_{66}Of_{34}$	–	–
MODES					
Plagioclase	90·90	85·80	74·20	69·00	79·90
Hypersthene	0·30	4·90	1·00	–	1·50
Hornblende	6·00	6·20	20·40	26·40	14·80
Ores (Ilmenite and Magnetite	1·30	1·90	2·40	3·00	2·10
Biotite	–	0·20	–	–	–
Calcite	0·80	0·30	0·80	0·80	0·70
Scapolite	0·70	0·70	1·20	0·50	0·80
Sphene and Apatite	–	–	–	0·30	Tr

K.29 Anorthosite. K.10 Noritic Anorthosite.
K.23. Gabbroic Anorthosite. K.32 Anorthositic gabbro.

have nearly equal distribution within the mass, and hence the bulk composition of the whole mass is indicated by the average of the analysed specimens. In Table 3 the analyses of Kadavur rocks are shown together with comparable analyses of anorthosites from Adirondacks, Bergen, Bengal, Daly's average for 12 anorthosites, and Nockolds' average of 9 anorthosites from massifs. In general the composition of the Kadavur rocks compare well with those from other areas, but show a peculiarity in having a higher MgO : FeO ratio. No. 12 in Table 3 is the average composition of the Kadavur mass, while No. 13 is the composition of gabbroic anorthosite postulated by Buddington (1939, p. 235) to be similar to the primary magma from which Adirondack anorthositic rocks were derived, and No. 8 the

TABLE 2.—ESTIMATED MODES OF ROCKS FROM THE CORE TO THE PERIPHERY OF THE KADAVUR MASS

	Core			*		*		*	*	Periphery	
	1	2	3	4	5	6	7	8	9	10	11
Feldspars	99·0	96·0	93·0	90·9	90·0	85·8	80·4	74·2	69·0	58·2	50·0
Mafics (Ortho and clinopyroxene +hornblende)	0·5	2·6	3·8	6·3	7·0	11·1	16·4	21·4	26·4	36·2	44·8
Ores, calcite, scapolite, etc,	0·5	1·4	3·2	2·8	3·0	3·1	3·2	4·4	4·6	5·6	5·2

* 4, 6, 8 and 9 are the analysed specimens K.29, K.10, K.23 and K.32.

MODAL COMPOSITION OF ILMENITE-MAGNETITE-PYROXENITE

	1	2
Hornblende . . .	11·4	–
Clinopyroxene . . .	25·9	32·0
Orthopyroxene . . .	28·3	26·4
Ores (Ilmenite + magnetite) .	34·4	41·6
Orthopyroxene . . .	$En_{40}Of_{60}$	$En_{42}Of_{58}$

composition of gabbroic anorthosite from the Kadavur mass. While the above analyses show a general similarity, the main difference between the composition of the Kadavur mass and the composition of the Adirondack magma is in the higher MgO : FeO ratio of the former. The normative plagioclase in Buddington's gabbroic anorthosite is $An_{56}Ab_{44}$, but in the Kadavur rocks, the normative plagioclase is $An_{66}Ab_{34}$ though the modal composition is around An_{50} to An_{55}. No. 1 in Table 3 is anorthosite from Kadavur, and is very similar to the average composition of anorthosite given by Daly (No. 3), and differs from the composition of labradorite rock from Bergen (No. 2), in having a higher MgO : FeO ratio. It may be seen, however, that the Kadavur rocks are similar to anorthositic rocks of the Adirondack type in chemical composition.

Norm and Mode. A comparison of the normative and modal compositions of the analysed rocks, shown in Table 1, brings out some

TABLE 3.—COMPOSITION OF KADAVUR ROCKS WITH COMPARABLE ANALYSES

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	50·59	52·80	50·40	52·20	51·57	53·21	53·18	51·39	50·96	50·62	53·22	51·04	53·40	54·54
TiO_2	0·19	—	0·15	Tr	0·25	0·24	0·45	0·24	0·73	0·33	0·69	0·25	0·77	0·52
Al_2O_3	29·00	28·57	28·30	27·48	25·83	26·64	23·25	22·20	21·26	21·78	20·03	24·70	23·96	25·72
Fe_2O_3	1·17	0·19	1·06	1·33	1·66	0·35	1·53	1·19	1·82	1·37	0·70	1·35	0·91	0·83
FeO	0·94	0·43	1·12	0·56	1·63	1·24	1·82	3·13	4·37	3·29	3·98	2·25	3·02	1·46
MnO	0·02	—	0·05	—	0·04	0·02	0·11	0·07	—	0·06	0·09	0·05	—	0·02
MgO	1·17	0·27	1·25	0·14	3·18	1·16	2·60	5·30	4·49	5·95	4·08	3·90	1·88	0·83
CaO	12·11	12·17	12·46	13·00	11·86	11·48	11·18	11·98	11·46	12·06	12·33	12·00	9·85	9·62
Na_2O	3·48	4·82	3·67	3·99	3·23	4·75	3·97	2·94	3·17	2·78	3·57	3·11	4·17	4·66
K_2O	0·29	0·56	0·74	0·49	0·33	0·69	0·86	0·30	0·61	0·43	0·55	0·34	0·80	1·06
CO_2	0·49	—	—	—	0·21	—	0·34	0·41	0·27	0·37	0·38	0·37	—	—
P_2O_5	0·06	—	0·05	0·02	0·05	0·03	0·09	0·07	0·08	0·05	0·02	0·06	0·18	0·11
H_2O^+	0·75	N.D.	0·75	0·55	0·44	0·33	0·98	0·69	0·38	0·55	0·73	0·61	0·69	0·63
H_2O^-	0·11	N.D.		0·22	0·08	0·04	0·15	0·05	0·05	0·13	0·06	0·09		
Cl	0·05	—	—	—	0·04	—	—	0·03	—	0·04	—	0·04	0·43*	—
S	—	0·24	—	—	—	0·03	Tr	—	—	—	—	—	—	—
Less "O" for Cl	0·01	—	—	—	0·01	—	—	0·01	—	0·01	—	0·01	—	—
Total	100·41	100·05	100·00	99·98	100·39	100·20	100·51	99·98	99·65	99·80	100·43	100·15	100·06	100·00

* Other constituents.

1. Rock. K.29. Anorthosite, Kadavur. 2. Labradorite Rock from Bergen, Washington (1919), p. 302. 3. Daly's average of 12 anorthosites, Johannsen (1937), p. 201. 4. Labradorite rock. Raniganj, Chatterjee (1936), p. 34. 5. Rock. K.10. Noritic Anorthosite, Kadavur. 6. Anorthosite, Adirondacks, Buddington (1939), p. 30. 7. Gabbroic anorthosite, Adirondacks, Buddington (1939), p. 24, table 3. 8. Rock. K.23. Gabbroic Anorthosite, Kadavur. 9. Feldspathic gabbro, Adirondacks, Buddington (1939), p. 52. 10. Rock. K.32. Anorthositic gabbro, Kadavur. 11. Anorthositic gabbro, Adirondacks, Buddington (1939), p. 36. 12. Average composition of Kadavur rocks, taking their relative spatial distribution. 13. Gabbroic Anorthosite postulated by Buddington to be similar to the primary magma from which Adirondack anorthositic rocks were derived, Buddington (1939), p. 235. 14. Nockolds' average of 9 anorthosites in massifs, Nockolds (1954), p. 1020, table 7.

significant facts. The normative plagioclase in all rocks is An_{66}, but the modal plagioclase varies between An_{50} and An_{58}. It is possible that some of the normative anorthite has combined with the pyroxenes to give rise to the green hornblende, which is a subcalcic variety as seen from its optical characters. The normative orthopyroxene is richer in 'En' content than the modal orthopyroxene. and some of the magnesia may have gone into the hornblende. The normative potash feldspar is presumably in solid solution in the modal plagioclase though occasional spindles of microcline are present in some of the plagioclase plates.

Origin

The origin of anorthosites and related rocks has been discussed by several petrologists. However, the views presented by Buddington (1939) in the light of intensive field and laboratory study of the Adirondack anorthosites, offer perhaps the most satisfactory explanation for the origin of anorthosites under different environments. Buddington (1939, p. 208) has suggested two contrasted sets of relationship in which anorthosites and gabbroic rocks are found :—

(1) As major facies of strongly differentiated stratiform sheets with contrasted rock facies in layers, such as the Bushveld, Stillwater and Bay of Island complexes.

(2) As masses of small to very large areal extent without pronounced layering, such as the anorthosite massifs of Adirondacks, Quebec, Labrador and Laramie range in America, Bergen and Egersund in Norway and Volhynia in U.S.S.R.

The plagioclase in the first type of occurrence ranges in composition from An_{60} to An_{30}, with the sodic type coming up in the rocks of the uppermost parts of thick strongly differentiated sheets. The plagioclase in the second type varies in composition from An_{25} to An_{65}, generally being An_{50} Ab_{50}, the rocks themselves being pyroxene anorthosites. Buddington (1939, p. 209) has indicated in detail, reasons for establishing two contrasted modes of occurrence of anorthosites. He believes that the second type of anorthosites, which may be called the Adirondack type, has resulted from differentiation of a primary magma with the composition of a gabbroic anorthosite. By analogy to stratiform sheets, crustal layering with a bytownite-anorthosite horizon is visualized; approximating in composition 92 per cent bytownite-labradorite (An_{70}) and 8 per cent. pyroxene. Partial melting of this horizon at a temperature of 1350°C. would yield a liquid consisting of 80 per cent andesine-labradorite ($An_{50}Ab_{50}$) and 20 per cent pyroxene, approximating a gabbroic anorthosite in bulk composition. Fusion and partial melting of the bytownite-anorthosite layer of the crust would result in generation of gabbroic anorthosite magma which in turn would differentiate and give rise to large massifs

of anorthosite with subordinate gabbroic facies. The fact that all the known occurrences of the Adirondack type of anorthosite have been emplaced in pre-Cambrian times favours Buddington's hypothesis. According to Buddington (1939, p. 220) :—

> "If the primary magma, from which the anorthosite and its related rocks were derived, were thus dependent in some way upon the isogeotherms during pre-Cambrian times being locally higher and permitting derivation of a magma in part from an anorthosite-bearing horizon above the general peridotite zone, lower temperature gradients in the earth's crust during subsequent time would then afford an explanation for the almost, if not complete, absence of anorthosite of the Adirondack type in post pre-Cambrian times.',

Fowler (1930, p. 399) discussing the origin of the anorthosites of Laramie Mountains has also favoured the theory of the anorthosites having been intruded as a magma, with later differentiation. In the present instance the foliated margins of the Kadavur mass, the protoclastic structures seen in the anorthosites, the differentiation of the anorthosite into a gabbroic facies, and the presence within the anorthosites of layers and lenses of ilmenite-magnetite pyroxenite, indicate the Kadavur mass to have intruded as a magma of anorthositic composition. The almost uniform composition of the plagioclase (An_{50-60}) in these rocks, and the absence of any stratiform layering, suggest these anorthosites to be of the Adirondack type. The volumetric distribution of anorthosites within the mass in relation to gabbroic rocks, and the total absence of any granodioritic or syenitic differentiates within the mass, also strongly favour the hypothesis of the original magma having been anorthositic in composition during intrusion. The possibility of the Kadavur mass being only a satellite of a much larger pluton of anorthosite in an adjacent area, like the Carthage mass in the Adirondacks, cannot be ruled out; future mapping in the adjacent terrain will help in resolving this possibility. The Kadavur mass is the first recorded occurrence of the Adirondack type of anorthosite in the Archaean of Southern India. The petrology and chemistry of the rocks of this mass support Buddington's hypothesis for the formation of anorthosites and related gabbroic rocks from a gabbroic anorthosite magma.

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EXPLANATION OF PLATE X

Rocks from the Kadavur intrusion, Madras.

Fig. 1.—Plagioclase crystals showing protoclastic granulation, in anorthosite. Crossed nicols. × 10.

Fig. 2.—Large plate of orthopyroxene with platy inclusions of a micaceous mineral and insets of clouded plagioclase. × 15.

Fig. 3.—Ilmenite-magnetite pyroxenite, showing the ores replacing earlier silicates. × 6.

Fig. 4.—Granulitic anorthositic gabbro from the marginal facies. × 6.

FIG. 1.

FIG. 2.

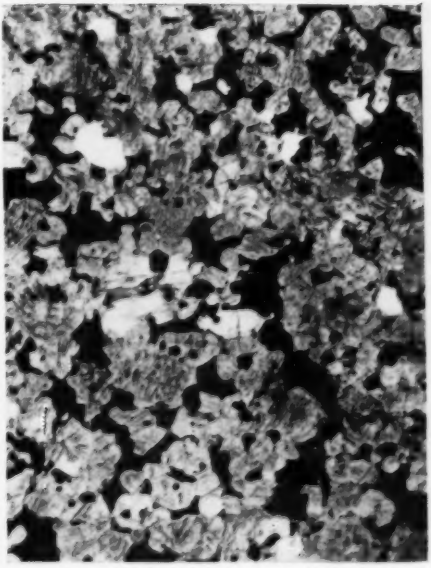


FIG. 3.

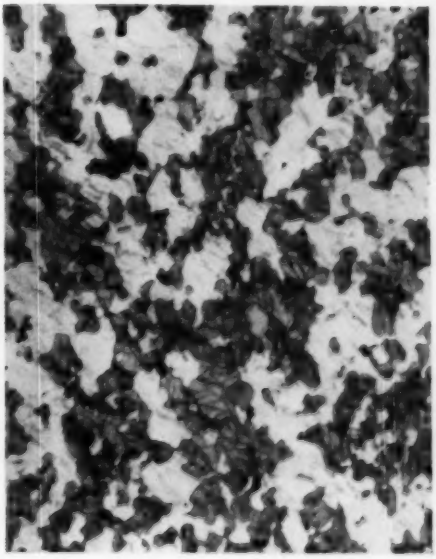


FIG. 4.

ROCKS FROM THE KADAVUR INTRUSION.

Structural Geology of the Manx Slates

By J. E. Gillott

(PLATE XI)

Abstract

Structures including folds, cleavages, faults, joints, and lineations are described. Three periods of folding are distinguished to which three cleavages are related. In order of decreasing age the cleavages are flow-cleavage, fracture cleavage, latest fracture cleavage. The main fault systems trend north-north-east, approximately east-west, and north-west. Joints follow two principal directions. These are north-west—south-east, and north-east—south-west. The dominant lineation is north-east—south-west. At right angles to this is a north-west—south-east lineation which affects all visible foliation. It is confined to a faint crinkling.

Introduction

THE most comprehensive account of Manx geology is contained in the Survey Memoir " The Geology of the Isle of Man " (Lamplugh, 1903). This contains complete references to previous work.

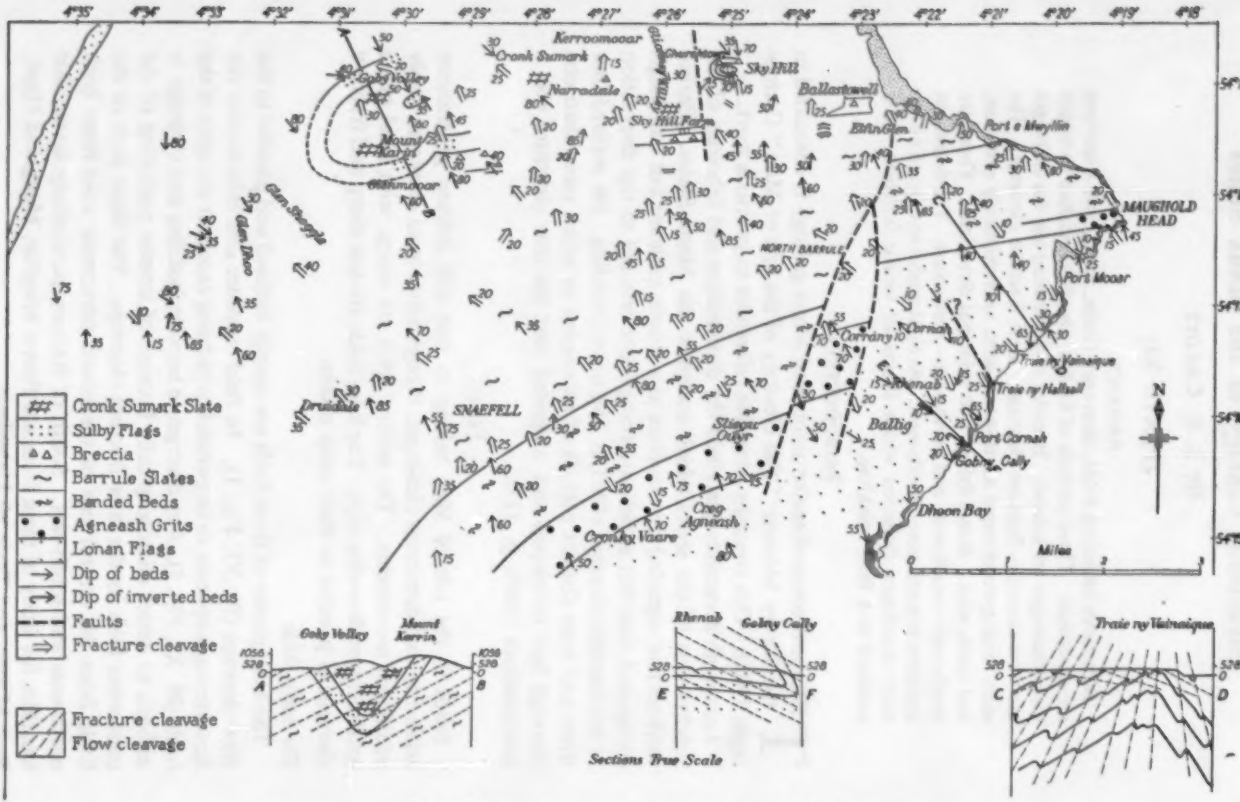
Lamplugh accurately described the distribution and lithology of the subdivisions of the series which comprise the Manx Slates. Earlier workers had regarded the structure as a simple anticline but Lamplugh recognized that this anticlinal arrangement referred to the disposition of the fracture cleavage (1903, p. 85), not to bedding. He realized that there had been distinct periods of movement in which more than one cleavage had developed and suggested that the true structure was a synclinorium (1903, p. 117).

Folds

Folds in the Isle of Man belong to two well defined generations related to two dominant cleavages, though other local cleavages imply additional movements. The earliest folds are sharp, with axial plane schistosity or flow-cleavage. The later folds are less sharp and fracture cleavage is parallel to their axial planes.

The early folds

The axial planes of these folds are steeply inclined and parallel to the flow-cleavage (Pl. XI, Fig. 1). In field exposure and thin section the flow-cleavage appears to lie parallel to bedding except at the apex of the folds (Pl. XI, Fig. 3). Any divergence between bedding and cleavage is difficult to detect microscopically because of intense puckering of the micaceous folia by the later fracture cleavage. The short limb of the folds faces the central axis of the island (structural axis) from both north-west and south-east. South of Ramsey particularly favourable localities for study of these folds are Port-e Mwyllin, Maughold Head, Port Mooar, and Traie ny Uainaigue.



TEXT-FIG. 1.—Map of the Maughold Head–Suley Glen Area, Isle of Man.

Intermediate folds

Nearly upright folds are occasionally exposed as for example at Port Mooar. At the south-east of this inlet they are overturned to north-west but at the north-west they are overturned to south-east. The folds' steep axial planes suggest that they date from the oldest movements but flow-cleavage, as seen in section, does not lie parallel to their axial planes and instead a wide-spaced fracture cleavage is parallel to this plane.

Overturned folds

Younger folds with axial planes parallel to the regional fracture cleavage are more common than those above described. The short limbs face away from the structural axis to north-west and to south-east. These directions are in each case opposite to those of the early folds (Pl. XI, Fig. 2).

Cleavages

Flow-cleavage

Flow or slaty cleavage forms the earliest planes of parting in the Manx Slates. It has a dip of about 55–60 degrees to north-west in the north-west of the island and a similar inclination to south-east in the south-east of the island (Text-fig. 2). The frequent vertical dips on bedding (flow-cleavage virtually parallel) in the axial region of the island, as along the Baldwin Valley (Lamplugh, 1903, p. 159) indicate that this cleavage has the form of an inverted fan.

Fracture cleavage

Fracture cleavage is in many areas the most prominent foliation. Dips measured on fracture cleavage were the basis for the early view that the structure of the area is a simple anticline. It has a general north-west inclination of about 25–30 degrees in the north-west of the island and a south-eastern dip at a similar amount in the south-east. It has a shallow inclination in the axial belt. The fracture cleavage is often more properly described as shear cleavage.

Shear cleavage

In the northern part of the Manx Slates the early flow-cleavage is intensely puckered by shear cleavage in which a film of platy minerals lies parallel to the shear planes (Mead, 1940, p. 1010 ; Hills, 1955, p. 109). When closely spaced this structure tends to obliterate pre-existing flow-cleavage and Broughton (1946, p. 13) believes that it can be transitional between fracture and flow-cleavage. Where the shearing out of micas in the new direction has been most intense, it is evident that had the structure developed much further no trace of earlier flow-cleavage would have remained. In the south-central part of the Manx Slates recrystallization has been more prolonged and more intense than

in their northern part. At Archallagan the dominant foliation is a gently inclined schistosity. Its low inclination suggests a correspondence with the fracture or shear cleavage of the axial belt in the northern part of the island. Slides from specimens which surround Archallagan show that the fracture cleavage becomes less intense as the recrystallization intensifies and this suggests that the schistosity developed via the sequence fracture cleavage—shear cleavage—schistosity, as suggested by Broughton (1946, p. 13). To the south of the

TEXT-FIG. 2.—Structural map of the Manx slate series.

Foxdale granite the recrystallization has been less extreme and though garnets and cordierite are present, planes of dark inclusions occur which possibly represent healed fracture cleavage. These planes dip at about 10 degrees to south-east and conform to the regional pattern of fracture or shear cleavage. On South Barrule and farther to the south-west towards " The Stacks ", cleavage dips at about 20 degrees to north-west. Microscopically, fracture cleavage can be seen to be quite lacking and the gently dipping cleavage is a flow-cleavage. Its inclination agrees with the regional pattern of the fracture or shear cleavage and it seems probable that it formed in the same period of movements.

Steeply inclined fracture cleavage

In addition to the dominant fracture cleavage, an earlier one also exists (Pl. XI, Fig. 4). In Port Mooar there are near upright folds, to the axial planes of which an early fracture cleavage is parallel (vid. sup.). A steeply dipping fracture cleavage has been found in slides from specimens from other parts of the Manx Slates, and so far as present evidence goes it seems most common in the region of the structural axis.

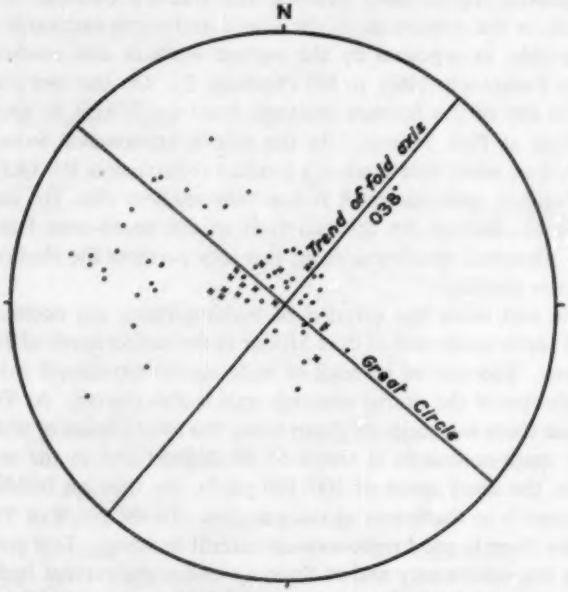
Regional Tectonics

The general dip of both bedding and fracture cleavage is north-westwards in the north-west of the island and south-eastwards on the opposite side, as reported by the earliest workers and confirmed in detail by Lamplugh (1903, p. 85) (Text-fig. 2). On the east coast the change in dip of the fracture cleavage from north-west to south-east takes place at Port Mooar. As the axis is approached from either north-west or south-east there is a gradual reduction in the inclination of the fracture cleavage until it has very shallow dips (10 degrees). The axis of cleavage-dip reversal runs inland south-west from Port Mooar. Oriented specimens from this axis confirm the shallow dips on fracture cleavage.

On the east coast the reversal of bedding-plane dip occurs a few hundred yards south-east of Port Mooar in the region north of Traie ny Uainaigue. The axis of reversal of bedding dip (structural axis) thus lies south-east of the similar cleavage axis in this region. At Traie ny Uainaigue there is a series of sharp folds, the axial planes of which are inclined south-eastwards at about 55–60 degrees and to the south of which, in the short space of 100–150 yards, the dips on bedding are predominantly to south-east at steep angles. To the north of Traie ny Uainaigue there is good right-way-up current bedding. This gradually becomes less satisfactory and at Traie ny Uainaigue current bedding is virtually absent, but grading appears in certain bands, in units 10–15mm thick or less, and becomes more common to the south. This indicates that the beds are right way up, with younger strata to south-east. The beds thus display a normal sequence to both south-east and north-west of the structural axis. About 2¼ miles south-west of Port Mooar, the Corrany area is in the region of reversal of dips of both cleavage and bedding. Low dips are common on the cleavage but farther north-west the angle of inclination becomes greater. Dips on bedding are variable in both direction and amount but farther north-west the dip is generally steep and to north-west.

The change of bedding-plane dip is most clearly seen on the coast near Traie ny Uainaigue. This change occurs when the axis of an anticlinorium is crossed (Text-fig. 1, Section CD). The folds constituting this anticlinorium belong to the earliest generation and, therefore, the

most important structural change which affects the bedding developed in the flow-cleavage movements. The north-western side of the anticlinorium, from youngest to oldest, consists of Cronk Sumark Slate, Sulby Flags, Breccia, Barrule Slates, Banded Strata, Agneash Grits and Lonan Flags. These have predominantly north-western dips. South-east dipping Lonan Flags occupy almost the whole of the opposite limb. Higher divisions are not exposed although they are perhaps partly represented in the south of the island at Langness and at Port Greenough where graded, right-way-up, banded slates occur. This suggests



TEXT-FIG. 3.—Trend of axis of Port Cornah Syncline (plunge zero).
● Poles to bedding.
+ Poles to fracture cleavage.

that the anticlinorium extends to the south of the island and that these beds are the south-east dipping equivalents of the banded slates exposed on the north-western side of the structural axis. The south-east dipping flags at Douglas and Laxey are also right-way-up (current-bedding).

Port Cornah Syncline

About ½ mile north of Port Cornah, in the small inlet of Traie ny Halsall, the beds show right-way-up graded and current bedding. Occasional evidence found along the coast to the south shows that the sequence remains normal to about 450 yards north of Port Cornah. There current bedding is inverted. Similar evidence of inversion was

observed at frequent intervals as far south as Gob ny Cally, where there is probably a fault, since south of an exposure gap 30–40 yards wide a different type of flags occurs, more homogenous than to the north, and without current bedding. The right-way-up beds south of Traie ny Halsall dip gently (15–20 degrees). Flaggy beds exposed in the stream draining down to Cornah and in the parallel stream to the south (Rhenab or Glen Mona), also show poor right-way-up current bedding. The inverted strata of Port Cornah dip steeply (70 degrees). Lamplugh linked these beds with those exposed along Rhenab (1903, p. 144) but this is inconsistent with the way-up evidence.

Fracture cleavage dips regularly at about 25 degrees throughout this area and is thus steeper than the shallow dipping upright beds, but is less steep than the inverted strata.

On the coast, between the normal and inverted beds, a great many loose blocks obscure the exposures and the possibility of concealed faults in this area has to be considered, but the facts, as outlined above, appear broadly explainable on the assumption of an overturned syncline closing to the south-east and formed during the movements in which the fracture cleavage developed. On this hypothesis the overturned strata of the Gob ny Cally–Port Cornah area represent the steeply dipping upper limb of the syncline and the slightly inclined upright beds of Traie ny Halsall–Rhenab and the parallel stream to the north, the flat-lying, lower limb of the fold. It is also probable that the strata exposed in the streams draining down to Ballig, farther west, owe their shallow dips to the continuation of the lower limb of the same structure. On the assumption that the fold dates from the fracture cleavage movements, the relationship between this cleavage and both the overturned and upright beds, at once becomes clear, for this is a consequence of its parallelism to the fold's axial plane (Text-fig. 1, Section E–F).

The plunge, as determined stereographically, is zero and the trend is north-east–south-west (Text-fig. 3). This agrees with the trend of the minor folds to the south of Port Cornah which, however, have a gentle plunge to the south-west. These indicate steeply inclined overthrust to south-east, which agrees with the outward movement to be expected from the trough of the major syncline.

The beds to the north of Traie ny Halsall do not appear to be involved in the fold since, though they young to the south-east, which would place them on the fold's flat-lying limb, the dips are steep and sometimes vertical. Furthermore, folds related to the fracture cleavage, occurring south of Traie ny Uainaigue, indicate drag movements with over-thrusting to south-east if regarded as drag folds, and this is in the opposite sense to that which would have been expected on the lower limb of the syncline. It therefore seems probable that a fault of some

magnitude reaches the coast at Traie ny Halsall and by facilitating erosion is responsible for the inlet.

Lamplugh remarked that there was something " peculiar in the structure and composition of these rocks " (1903, p. 144) but the postulated syncline seems to account for many of the " peculiarities " of the region.

Sky Hill—Gob y Volley—Kirkmichael Syncline (Text-fig. 1, Section A–B)

As one ascends the northern slopes of Sky Hill the bands crossed are breccia, slate, breccia (interbedded with a thin zone of graded sediments) and flags. Dips are to south-east, but as the band of flags, exposed on the flatter ground of the summit of the hill, is crossed, the dip reverses to north-west. This suggests that the flags lie in the trough of a sharp syncline. South of the band of flags, breccia (in contact with the flags) and slate is exposed. The successions to the north and south of the trough are therefore similar. Farther south, outcrops of breccia surrounded by slate, perhaps represent upfolds of the lowest northern horizon of breccia. The north-westerly dips are lower than the corresponding south-easterly ones and the bands have a wider outcrop.

The deduced order of succession (Gillott, 1956) indicates that the beds to the south of the synclinal trough are right-way-up, but way-up evidence has not been found at this locality. The south-east dipping sediments interbedded with the breccia on the northern slopes of Sky Hill show right-way-up, graded bedding.

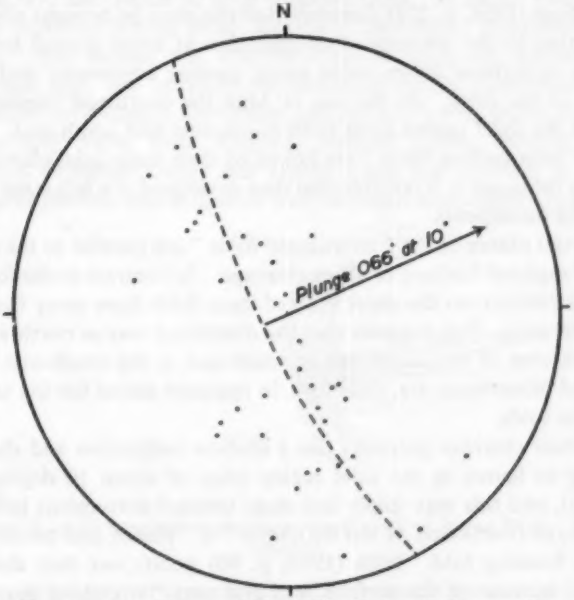
On the west of Sky Hill the strike shows the nose-shaped form of a plunging fold and the whole succession is closed east of Glionney Killey, where the next exposures are situated. To the west and south there are small exposures of breccia and slate.

South of Sky Hill farm there is a north-west dipping sequence of breccia (oldest), slate, breccia, flags (youngest), similar to that exposed on Sky Hill. The two highest members—breccia, flags—of this Sky Hill farm succession pass abruptly eastwards into thinly bedded slate and it seems likely that the junction is faulted. This suggests that the Sky Hill farm succession represents the downthrown southern limb of the Sky Hill syncline. Hence the fault may continue northwards.

On this interpretation the slate and breccia to the west of Sky Hill will be younger than any beds exposed on Sky Hill itself. This postulated extension of the fault also clarifies the distribution of metamorphic minerals (Gillott, 1955, Text.-fig. 1). Biotite occurs on Sky Hill but is absent west of the postulated fault. This biotite is north of its general regional limit and may be accounted for by the apparent lateral shift to the north of beds within the biotite isograd. Conversely,

the development of biotite in rocks at Sky Hill and Sky Hill farm supports their correlation.

South-east dipping flags reappear to the west on Gob y Volley, approximately where one would anticipate flags after allowance for the fault and the plunge of the fold (Text-fig. 4). Indistinct current bedding indicates that the beds are right way up. Westwards the strike swings round to north-north-east, suggesting closure. North-west dipping flags, right way up, outcrop on Mount Karrin and east of



TEXT-FIG. 4.—Plunge of Sky Hill—Gob y Volley syncline.
● Poles to bedding.
– – – Great circle.

Sulby Glen and may be the continuation of the flags on Gob y Volley (Text.-fig. 1, Section A–B).

To the south-west in Glen Shoggle, Glen Dhoo (now known as Ballaugh Glen) and Glen Wyllin, south-east dipping slate is exposed. In each case north-west dips occur a short distance to the south-east, suggesting the continuation of the syncline to the west coast of the island. The trough of the syncline is displaced to the south, probably indicating faults.

This syncline, therefore, extends for a total distance of about eight miles and occupies what in pre-glacial times was the northern coast. Hence it is comparable with the east coast syncline (Clifton Ward, 1880, p. 1–9 ; Lamplugh, 1903, p. 151–55) both in length and position.

Mechanics of Folding

In the north-east of the island the axial planes of the earliest generation of folds are parallel to the steeply inclined (55–60 degrees) flow-cleavage. The steep limb of the folds faces the structural axis from both north-west and south-east.

The flow cleavage suggests north-west–south-east compression normal to the general trend of the folds. The inclination of the axial planes suggests that a couple was superimposed on the compression, and Billings (1954, p. 228) proposes that this may be brought about by a reduction in the intensity of compression at lower crustal levels so that the uppermost layers move more, causing asymmetry and overturning of the folds. In the Isle of Man the overthrust implied was towards the axial region from both north-west and south-east.

The " intermediate folds " are linked by their steep axial planes with the early folds and it is possible that they developed at a late stage in the early fold movements.

The axial planes of the " overturned folds " are parallel to the gently inclined regional fracture or shear cleavage. In contrast to the folds of the early movements the short limb of these folds faces away from the structural axis. This suggests that the overthrust was to north-west in the north-west of the island and to south-east in the south-east. The suggested movements are, therefore, in opposite senses for the earliest and latest folds.

The shear cleavage generally has a shallow inclination and shows a tendency to flatten in the axial region (dips of about 10 degrees are common), and this may imply late stage upward movements in which the cleavage functioned as the dominant " s " planes and produced a regional bending fold. Hills (1955, p. 90) points out that this will cause an increase of the surface area and that " stretching may take place by flowage from the anticlinal crest towards the limbs of the fold, giving a supratenuous fold, or by normal faulting ". Flowage from the axial region of the Isle of Man will account for the movement directions of the overturned folds related to the shear cleavage.

Succession of Movements

The cleavages are related to a definite sequence of movements and this may now be summarized :

1. Sharp folding occurred with the development of flow-cleavage.

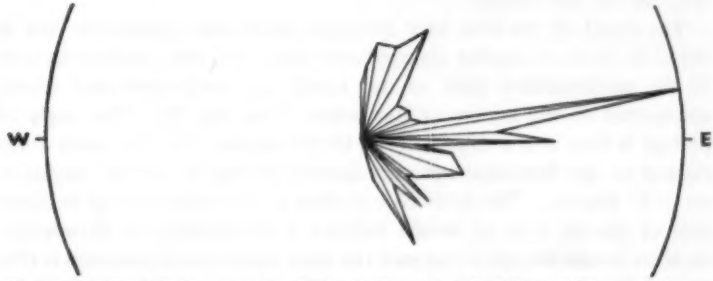
2. Near upright folds and a patchily distributed, steeply inclined, fracture cleavage developed.

3. The regional fracture cleavage developed, dipping at low angles to north-west in the north-west of the island and to south-east in the south-east.

Faults

Faults in the Isle of Man cause numerous clefts in the coastal exposures but they generally produce no effect from which throw or movement direction can be estimated. The most common trends are north-north-east, approximately east-west, and north-west (Text.-fig. 5). In the northern part of the island the majority hade at a low angle but some high angle thrusts have been seen, and Lamplugh (1903, p. 87) also refers to such displacements. It seems likely that faulting occurred during three periods—Caledonian, Hercynian, and Tertiary. The thrusts and north-east strike faults are probably of Caledonian age, the north-south—east-west faults (associated with mineralization) probably Hercynian, and the north-west faults Tertiary.

Proceeding south from Ramsey, Barrule Slates, Banded Beds, Quartzites (Agneash Grits) and Lonan Flags are exposed in order. Westwards this succession is twice stepped south-westwards, apparently



Text-fig. 5.—200 bearings on faults in North-east of Isle of Man. 5 degree interval.

by concealed faults. The same succession occurs in the area of Corrany and again, beyond a further break, in the Slieu Ouyre district. The succession then strikes southwestwards without further displacement towards Cronk-y Vaare and beyond.

The structural axis is displaced relatively southwards, as are the beds, affording further evidence in support of the conclusion that to the south-west the coastal succession is faulted.

The precise position of these faults is not clear and topography gives little help. Low ground, which possibly indicates the course of the fault, occurs between North Barrule and Ballagilley and farther south ; the main road also follows low ground.

As reported by Lamplugh, a narrow outcrop of breccia is bounded by parallel faults south of Ramsey, 150 yards east of the commencement of rock exposures. The rocks south of Traie ny Halsall are probably separated from those to the north by a fault. The position of the landward continuation of this fault is not clear.

On Sky Hill is a succession, repeated south of Sky Hill farm possibly by faulting (see Text-fig. 1).

Joints

Vertical joints in the Isle of Man follow two principal directions. These are north-west–south-east and north-east–south-west (Text-fig. 2). The former group are cross, or " ac " joints and trend about normal to the strike of the fold axes. The other set intersects these at about 90 degrees and is longitudinal, lying parallel to the regional strike.

Lineation

The dominant lineation (Text-fig. 2) in the Manx Slates trends north-east–south-west and is Caledonoid in trend. The north-east–south-west lineation includes the strike of both minor and major folds and the intersection of cleavage and bedding. A lineation at right angles to this is also common. It is confined to a faint crinkling which affects all visible foliation and has therefore been produced at a late stage in the movements.

The trend of the fold axes averages north-east–south-west but in detail it shows a regular change from east-north-east–west-south-west in the north-eastern part of the island to north-north-east–south-south-west in the centre of the island (Text.-fig. 2). The angle of plunge is low and averages from 10–20 degrees, but the early folds related to the flow-cleavage occasionally plunge at steeper angles of up to 35 degrees. The folds do not show a systematic change in direction of plunge such as would indicate a culmination or depression. In areas where breccia is exposed the most pronounced lineation is that caused by the stretched fragments, the long axes of which strike N.E.–S.W.

Acknowledgments

I wish to express thanks to Prof. R. M. Shackleton who suggested the work and gave critical and helpful advice throughout. I wish also to thank the Birkenhead Education Committee for financial assistance.

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Geological Survey and Museum,
London.

FIG. 1.

FIG. 2.

FIG. 3.

FIG. 4.

FOLDS IN MANX SLATES.

EXPLANATION OF PLATE XI

FIG. 1.—View facing south-west of sharp syncline in Port-e Mwyllin. The axial-plane of the fold is parallel to the steep, north-west inclined flow-cleavage. This fold pre-dates fracture cleavage which, as can be seen in the photograph (e.g. near hammer), intersects bedding and dips at a low angle to the north-west. The incompetent argillaceous bands are greatly thickened in the axial region and slight thickening of the more arenaceous bands also occurs. In the lower part of the photograph there are quartz veins which are parallel to the fracture cleavage and higher up there are others which cut randomly across all structures.

FIG. 2.—The photograph is a view looking south, of the overturned folds exposed south of Traie ny Uainaigue. Fracture cleavage is parallel to the axial planes of the folds and is inclined at about 30 degrees south-east. The short limbs face south-eastwards and suggest south-easterly overthrust. The folds are in flags which show some thickening at the fold axes.

FIG. 3.—Enlargement of thin section made from specimen of fold illustrated in Fig. 1. The dark planes are fracture cleavage which obliquely intersect the bedding and axial plane of the fold. The flow-cleavage, parallel to the folds axial plane, can be seen in the photograph. Axial plane thickening of all bands can be seen, especially in the dark pelitic layers. The beds show small-scale slip movements on the fracture cleavage. Minute discontinuities of the beds are probably referrable to sedimentary creep.

FIG. 4.—Enlargement of slide from specimen of fold—Ballure Glen, Ramsey. This specimen is of particular interest as there are two fracture cleavages in addition to the flow-cleavage (parallel to bedding in photograph). The latest fracture cleavage is parallel to the axial plane of the fold. This cleavage displaces bedding and early fracture cleavage along minute slips. The earliest fracture cleavage is itself folded though the cleavage axis is shifted relative to the axis of the beds. On the left of the figure the early fracture cleavage displaces bedding along minute slips. The flow-cleavage lies parallel to the bedding and therefore the movements in which the early and late fracture cleavages developed both post-date those in which the flow-cleavage formed, so that there is evidence of three distinct movements : (1) Flow-cleavage movements ; (2) Early fracture cleavage movements ; (3) Late fracture cleavage movements. The latest fracture cleavage is parallel to the regional, gently inclined fracture cleavage so that the fold evidently dates from the regional fracture cleavage movements.

The Major Rock Groups of the Northern Red Sea Hills, Sudan

By B. P. Ruxton

Abstract

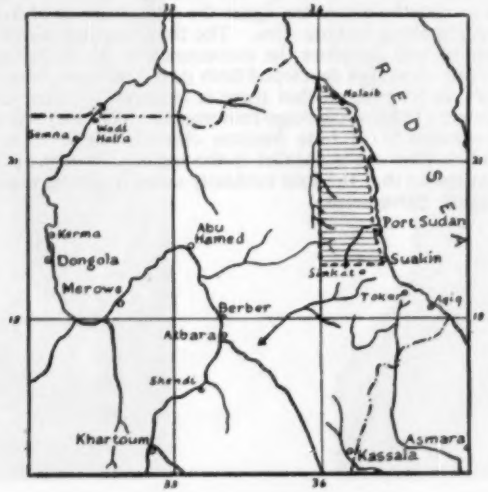
The Basement Complex rocks of the Northern Red Sea Hills, Sudan, are believed to be pre-Cambrian in age. They can be divided into three major sedimentary and volcanic divisions, with four main periods of igneous intrusion. The succession proposed by the author is as follows :—

Red granite.
Injection granite.
Awat series.
(Unconformity with folding, thrusting, and cleavage.)
Basic intrusive phase.
Nafirdeib series.
(Unconformity with folding, and regional metamorphism.)
Primitive system { Acid Gneiss (intrusive).
Schists and Gneiss.

Introduction

THE area of the Northern Red Sea Hills of the Sudan described is bounded by longitude 36° 00′ east, the Red Sea, and latitude 19° 00′ north (Text-fig. 1), and excludes the narrow coastal plain.

The author spent some twelve months in this area, and after carrying out a few general reconnaissance traverses over some 20,000 sq. miles, mapped 1,500 sq. miles in more detail.



TEXT-FIG. 1.—Location map of area described in North-East Sudan (scale approx. 1 : 15,000,000).

The 1 : 250,000 Sudan Survey Map Sheets are incomplete and considerable areas on them have never been surveyed. The detail on the surveyed areas includes only the correct location of some of the larger hills (jebels) accompanied by a rough sketch of the smaller hills and dry stream valleys (khors) ; however, the American Air Force carried out a trimetrogon aerial survey of the area during the war and these photographs were used for route finding, location, and geological mapping. The aerial photographs were taken in runs in a north-north-westerly direction across the hills at a height of 20,000 feet and the spacing between runs varies from ten to forty miles. The horizontal scale of the vertical photographs is approximately 1 : 32,000.

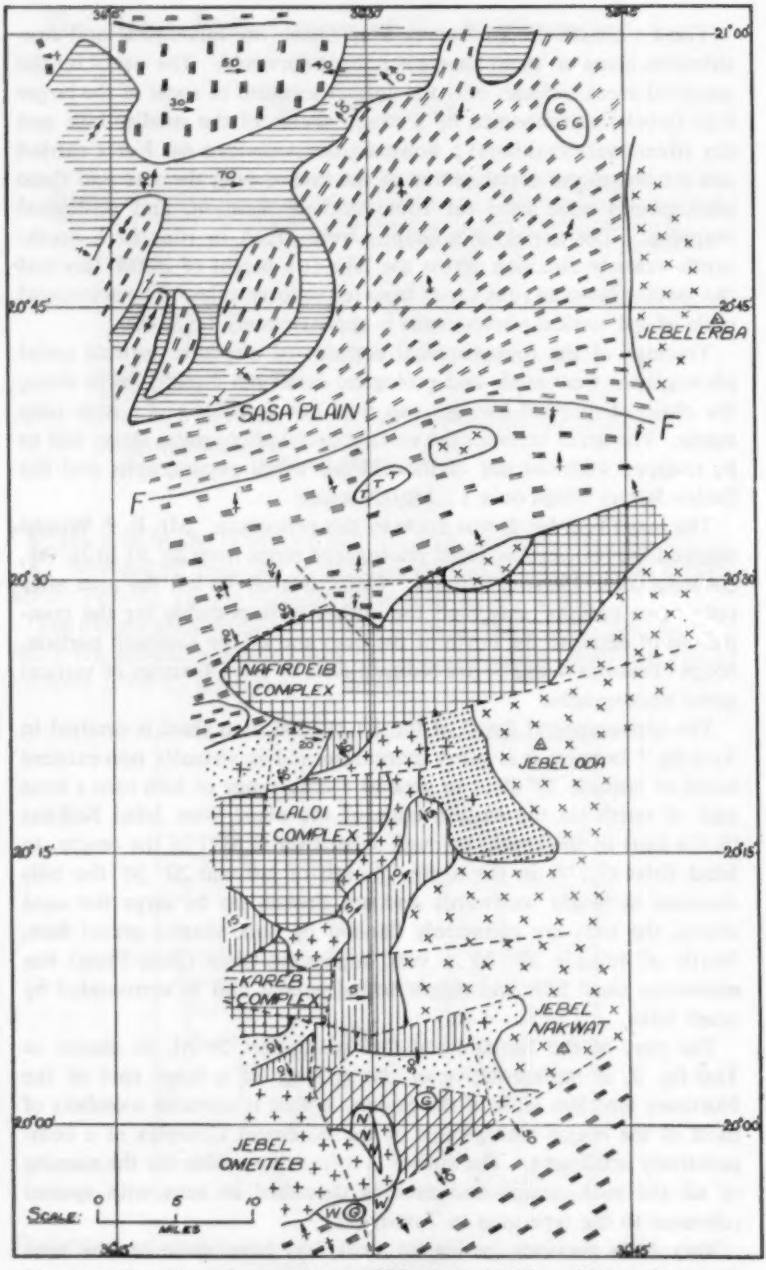
Tracings of the topographical features of alternate vertical aerial photographs were made and geological detail put directly on to these, the chain of mapped tracings was then put together and a strip map made. The areas between the vertical aerial photograph strips had to be mapped with the aid of the oblique aerial photographs and the Sudan Survey Maps on a 1 : 250,000 scale.

The map (Text-fig. 2) was made by this procedure. Mr. E. P. Wright mapped the two vertical aerial photograph strips from 20° 30′ to 21° 00′, covering some 350 square miles. Unfortunately he left the area after only three months' stay, and the author is responsible for the completion of detail to the north of the map and all the southern portion. Maps (Text-figs 4 and 5) are reduced directly from tracings of vertical aerial photographs.

The topographical detail of the 1 : 250,000 map sheet is omitted in Text-fig 2 because it is often inaccurate and is virtually non-existent north of latitude 20° 30′. In general a high range of hills runs a little east of north on the eastern edge of the map, from Jebel Nakwat (5,774 feet) in the south, through Jebel Oda (7,412) in the centre, to Jebel Erba (7,274) in the north. South of latitude 20° 30′ the hills decrease in height westwards and are broken up by large flat sand plains, the hills are commonly flanked by cone-shaped gravel fans. North of latitude 20° 30′ a very large sand plain (Sasa Plain) has numerous small hills and ridges dotted over it and is surrounded by small hills.

The part of the Muhammad Qol map sheet 36 M, as shown in Text-fig. 2, is representative of the geology of a large part of the Northern Red Sea Hills of the Sudan, in that it contains members of most of the major rock-groups of the Basement Complex in a comparatively small area. The author is solely responsible for the naming of all the rock-groups and each is described in turn with special reference to the type area in Text-fig. 2.

Very little previous geological work has been done on the area described ; however, the few publications pertaining to the general



TEXT-FIG. 2.—General map of part of Northern Red Sea Hills (scale approx. 1 : 750,000). See Text-fig. 3 for legend.

geology of the north-eastern Sudan are listed in the appended bibliography. Normally the publication of incomplete work of this kind is premature. Since so little is known of the geology of the Sudan, it is useful to attempt a preliminary analysis of some of the work accomplished. Unfortunately during the process of Sudanization most of the Geological Survey staff decided to leave the Sudan (myself included) and it may now be some time before any one of the large provinces is mapped and described.

The Basement Complex

In the north-eastern Sudan the Basement Complex is defined to include all the rocks underlying the Nubian sandstone. The patches of sandstone that do occur in this area have not yet yielded fossils and are correlated with the Nubian on lithological grounds only ; they are believed to be of Cretaceous age.

No fossils have hitherto been found in the sedimentary rocks of the Basement Complex and they are, therefore, tentatively classed as Pre-Cambrian ; however, the Injection and Red Granites, which are the newest rocks of the Basement Complex described here, may be of much later age.

The sedimentary and volcanic rock-groups were first proved to be " the right way up ", in many cases by structural methods, fracture cleavage and congruous dragfolds, and the law of superposition applied. The correct relation of the intrusives to the sedimentary and volcanic succession was more difficult, and in most cases only the older limit of age (post intruded group) was proved. For instance, the gabbros of the Basic Intrusive Phase are certainly post-Nafirdeib Series in age, but have not yet been proved to be of pre-Awat Series age. The sedimentary and volcanic succession compares with that proposed by Mr. G. Andrew for the Sudan north of latitude 6° N. (p. 95 Agriculture in the Sudan. Tothill, 1948). However, the lower unconformity between the Primitive System and the Nafirdeib Series is not yet finally proved and it may be some time before definite evidence is found to clarify the position.

Description of the Major Rock-Groups in the Muhammad Qol Area

The general sequence is believed to be as follows :—

9. Major faulting.
8. Acid and basic sills and dykes.
7. Red granite.
6. Injection granite—Large scale metasomatism.

5. Awat Series
   - (d) Massive acid volcanics.
   - (c) Silty mudstones and acid volcanics.
   - (b) Conglomerates.
   - (a) Massive silty mudstones.

   Uplift and erosion.
4. Basic intrusives.
   Large scale folding.
3. Nafirdeib Series [1]
   - Limestones, quartzites and pelites.
   - Intermediate volcanics and greywackes.
   - Basic and intermediate volcanics and greywackes.

   Uplift and erosion.

1 & 2 Primitive system.
   - 2. Basic dyke swarms.
     Large scale folding and regional metamorphism.
   - 1. (d) Granite pegmatites.
     (c) Acid Gneiss.
     (b) Schists and slates.
     (a) Hornblende schists and Gneiss.

1. *The Primitive System*

This system is defined as including all the rocks older than the Nafirdeib Series in the Northern Red Sea Hills. The type area is on Sasa Plain to the north of the Muhammad Qol Map Sheet, where there is a very clear succession of rock-groups :

Schists and slates	——— Top
Hornblende schists	
Acid Gneiss	——— Bottom

The acid gneiss is commonly composed of biotite granite gneiss and granodiorite gneisses. The mineralogy of these rocks is relatively simple ; quartz occurs in variable amount with orthoclase, oligoclase, and biotite ; muscovite is often developed near contacts. The biotite often occurs as lens-shaped clots, up to half an inch in length, aligned parallel to the foliation. Hornblende does not normally occur. In places the rocks lose their gneissose character and become massive and strongly lineated, sometimes with large phenocrysts of pink orthoclase. These rocks tend to form low rocky hills and sand or gravel plains.

The hornblende schists and gneiss are very variable in mineral constitution and texture. They invariably carry hornblende which may be alone, or, more commonly, accompanied by plagioclase,

[1] No internal succession has been worked out for the Nafirdeib Series and the three divisions given represent the author's opinion only.

quartz, biotite, and, locally, almandine garnet. Hornblende-plagioclase, hornblende-plagioclase-quartz and hornblendites are dominant as massive coarse-grained rocks or schists. Augen gneisses, with centres of hornblende mantled by biotite are notable, and marbles occur in two localities. The rocks tend to become enriched in biotite near contacts with the acid gneiss. Most of this series is very well banded, and each band has a different composition and/or texture and its strike conforms to the strike of the foliation. Foliation and/or lineation are usually present but sometimes masses of non-foliated and unlineated rocks occur. No original sedimentary structures were observed. The group forms low rounded hills commonly flanked by a mantle of black gravel.

The schists and slates are well bedded, low grade, regionally metamorphosed calcareous and argillaceous sediments. The schists are commonly sericitic, chloritic and talcose. Garnet schists, marbles, and small lenses of talc rocks occur locally. Fracture cleavage, slaty cleavage, rodding, and local contortion are common. The series has been shown to be the right way up from the evidence of small congruous dragfolds and fracture cleavage. They form low rounded hills which are commonly terraced or serrated due to the alternation of hard and soft bands.

The schists and slates overlie and interbed with the hornblende schists in the north-east of the area 36° 32′, 21° 00′ ; however, some ten miles W.S.W. of this they have a very sharp conformable contact, with no interbedding. The two series are folded into broad anticlines and synclines which show up well on the map and the fold axes plunge at a low angle in a northerly direction.

The contact between the hornblende schist and acid gneiss does not conform with this simple scheme. The hornblende schists always overlie the acid gneiss on the contacts and both rocks have concordant foliation and/or lineation. There is no gradation between the two rock-groups and the contact is always sharp and unchilled. There is no obvious injection of the hornblende schist by the acid gneiss ; however, masses of hornblendites and hornblende-plagioclase rock commonly occur throughout the gneiss, particularly near the contact ; some of these are up to 800 yards long and a few hundred yards wide. Also some of the patches of acid gneiss occur in the hornblende schist, but in this case they rarely occur more than about one mile from the contact and are not very large. It would appear that the acid gneiss was emplaced at depth under condition of stress and high temperature.

The three rock-groups all have a regional lineation of from 350° to 30°, generally about 10°. The regional strike of the foliation changes from E.–W., in the centre of the map, through N.E.–S.W., to N.–S., in the north of the map.

The acid pegmatites are of two kinds, an earlier set of white pegmatites with quartz, white orthoclase, muscovite, and occasional almandine, and magnetite. The muscovite crystals are up to six inches in length in places and sometimes small patches of muscovite rock occur. These pegmatites are from six inches to twenty feet wide and they are cut by the later pink pegmatites. The pink pegmatites carry quartz and pink orthoclase and, occasionally, a little muscovite. They vary in width from six inches to some thirty feet. Both sets of pegmatites run in random directions and in most places their outcrops are intermittent and lens-shaped, sometimes their margins show signs of strong shearing. They occur in a roughly circular area of about ten miles radius centred on 36° 25′, 20° 46′. They are abundant in the acid gneiss and common in the hornblende schist series in this area, but were not seen to cut the schists and slates.

2. *Basic Dyke Swarm*

In the Khor Lolignet area, 36° 35′, 20° 57′, a swarm of E.–W. dolerite dykes cut the acid gneisses and interbedded hornblende schists and slates ; they do not occur in the area of schists and slates shown on the map, nor in the intermediate volcanics of the Nafirdeib Series at the extreme north of the map. Another E.–W. swarm of porphyritic dolerite dykes occurs in the acid gneiss at 36° 21′, 20° 22′, and here the dykes end abruptly against the acid volcanics of the Awat Series. In both sets of dykes the separation distance between each dyke varies from 50-400 yards and the dykes themselves vary from 3 to 12 feet in width.

There is no proof that the dykes are younger than the pegmatites, as they do not occur together in the area. The fact that the dyke swarms have never been found cutting the Nafirdeib Series is no proof that they are older, and further work in the Red Sea Hills will have to be done before their exact relationship is known.

3. *Nafirdeib Series*

Just south of Gebeit Mine 36° 21′, 21° 00′ and running roughly along the 21st parallel of latitude, the schists and slates with north-south fold axes are overlain disconformably by the Nafirdeib Series with fold axes E. 30° N. The disconformity was traced some two miles by the author and it is believed to represent a major unconformity.

The Nafirdeib Series around Gebeit Mine are composed of green andesitic beds and greywackes with a pronounced development of epidote and chlorite ; they contain abundant quartz veins in places and the country rock around the veins is often rich in pyrite. Gold has been mined from these veins and from the pyrite-rich country rock. This series is folded into open anticlines and synclines with fold axes plunging at a low angle E. 30° N.

The type area occurs around Khor Nafirdeib at To-Olak, 36° 24′, 20° 30′. Here the beds are made up of green andesitic tuffs, agglomerates, and meta-andesites with minor quartzites, limestones, meta-dacites, and greywackes ; the common green colour is due to the pronounced development of chlorite and epidote, pyrites is commonly developed, especially in the more massive beds, and in places abundant quartz veins occur, some very large. A little to the east, in Khor Miseak, meta-basalts occur, often showing pillow structures.

At To-Olak, 36° 24′, 20° 30′, the series forms a large anticline plunging at about 20° along E. 30° N., and a well developed fracture cleavage is imposed parallel to the axial planes of the folds. Local shearing and small thrust faults parallel to the strike are common, and in places strong contortion and small dragfolds occur. On the whole the series is well bedded but, in places, massive blocky beds occur and the calcareous beds are commonly schistose. The Nafirdeib Series is at least 10,000 feet thick in this area.

At the south of the map another very large area of these rocks occurs, covering many hundreds of square miles ; the northern limit of its outcrop is shown on the map. The rocks are folded into large open anticlines and synclines plunging at a low angle along E.N.E., and are mainly composed of green tuffs, agglomerates, and meta-andesites ; however, thick beds of limestones, quartzites, and greywackes occur in places and these beds are thought to be high up in the series.

The Nafirdeib Series usually form fairly high rounded hills (over 3,000 feet in places) commonly mantled by a loose cover of angular scree. The limestones and quartzites usually form well marked ridges on these hills.

4. *Basic Intrusives*

In Khor Erkhab, 36° 42′, 20° 55′, a large gabbro mass occurs cutting the acid gneiss of the Primitive System.

At Dirbat Well, 36° 29′, 19° 55′, a small mass of norite outcrops cutting calcareous members of the Nafirdeib Series. The norite is a labradorite-hypersthene-ilmenite rock and in places, anorthosite and hypersthenite occur as bands or masses in it ; segregations and veins of ilmenite also occur. A skarn zone, some four square miles in area, has been produced from calcareous beds around the norite and it contains many large lenses of wollastonite rock. Other small bands and masses of monomineralic rock include grossular, schorlamite, idocrase, diopside and hydro-grossular (?).

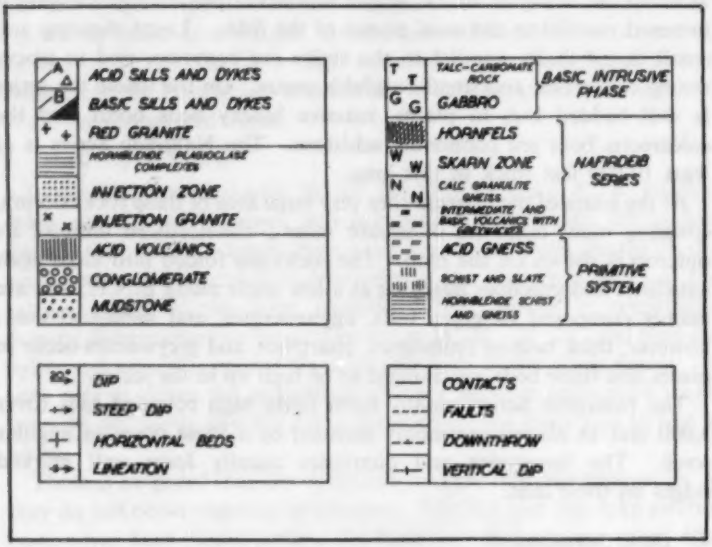
In Khor Burusia, 36° 30′, 20° 35′, talc-carbonate schists occur in the Nafirdeib Series. Four bands running in a N.E.–S.W. direction and dipping at a low angle N.W. occur. One is from 30 to 200 feet thick and can be traced for some 5,000 yards. The bands are made up of

talc-brucite-magnesite schist and the talc sometimes forms a white rock over 20 feet thick. Calcite is rare and the amount of lime is small. The rocks are thought to be derived from ultrabasic rocks cutting the Nafirdeib Series.

Basic intrusives have never been found cutting the Awat Series and for the moment they have been tentatively classified as older rocks.

5. *The Awat Series*

The type area of this series occurs on either side of the Khor



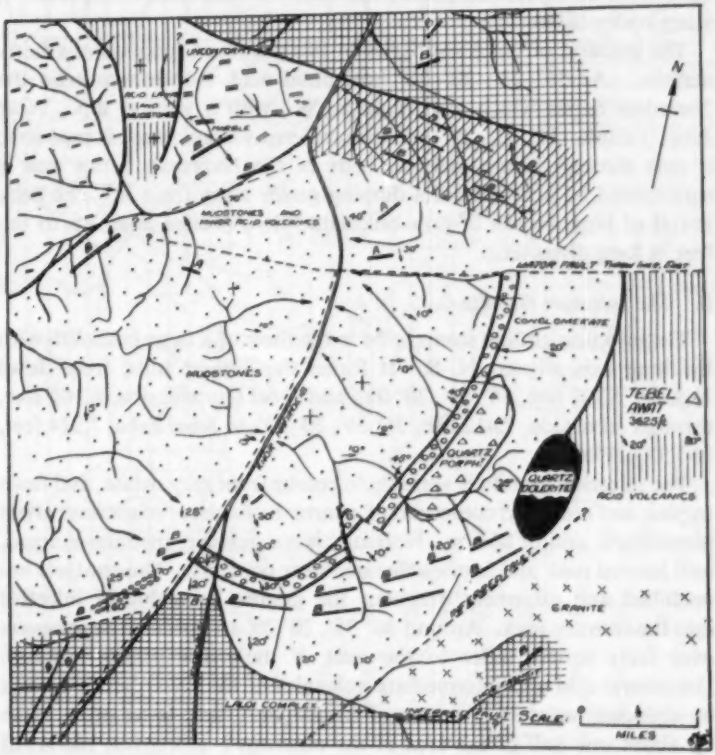
TEXT-FIG. 3—Legend for Text-figs. 2, 4 and 5.

Nafirdeib, 36° 25′, 20° 20′, near Jebel Awat (Text-fig. 4), and a very clear succession was observed.

Grey massive silty mudstones, some micro-conglomerates and a few andesite lavas occur at the bottom of the succession. They have no visible base and are at least 2,000 feet thick, and they are overlain sharply but conformably by a series of conglomerates some 400 feet thick. The matrix of the conglomerate is a silty mudstone and the pebbles embedded in it are up to two feet in long diameter, they are composed of abundant silty mudstones with meta-andesites, tuffs, agglomerates, porphyries, and granite. The conglomerate passes up abruptly into an interbedded series of silty mudstones and acid volcanics, and acid lavas soon become predominant. This series is at least 2,500 feet thick and the acid lavas include dacites, rhyo-dacites,

and rhyolites with interbedded tuffs and agglomerates. The lavas are predominantly grey in colour but may be purple, red, brown, and yellow; they are usually flow-banded and very often show fine flow-brecciation.

In Khor Gabideib, 36° 31′, 20° 05′, an interbedded series of mudstones



TEXT-FIG. 4.—Map of area between Laloi and Nafideib Complexes (Jebel Awat 36° 25′ E., 20° 20′ N.); scale approx. 1 : 100,000; see Text-fig. 3 for legend.

and acid volcanics occurs, and in places the mudstones have abundant clay ironstone nodules in them. It will be seen from the map that the Awat Series occurs in many other localities.

A significant feature of the Awat Series is their fresh appearance in hand specimen and unaltered nature in thin section. In the type area they occur as a semi-dome cut off to the north by a fault, and the change of dip is everywhere gradual; elsewhere their dip and strike is either fairly constant or changes slowly in any particular area. The

silty mudstones are very well jointed and the whole series shows some development of north–south fracture in places.

The mudstones and conglomerates form well rounded hills, and if flat lying a rectalinear drainage pattern is produced by the excellent jointing (Text-fig. 4). The acid volcanics, however, form high jagged hills (over 5,000 feet in places) and show a marked development of steep rocky cliffs.

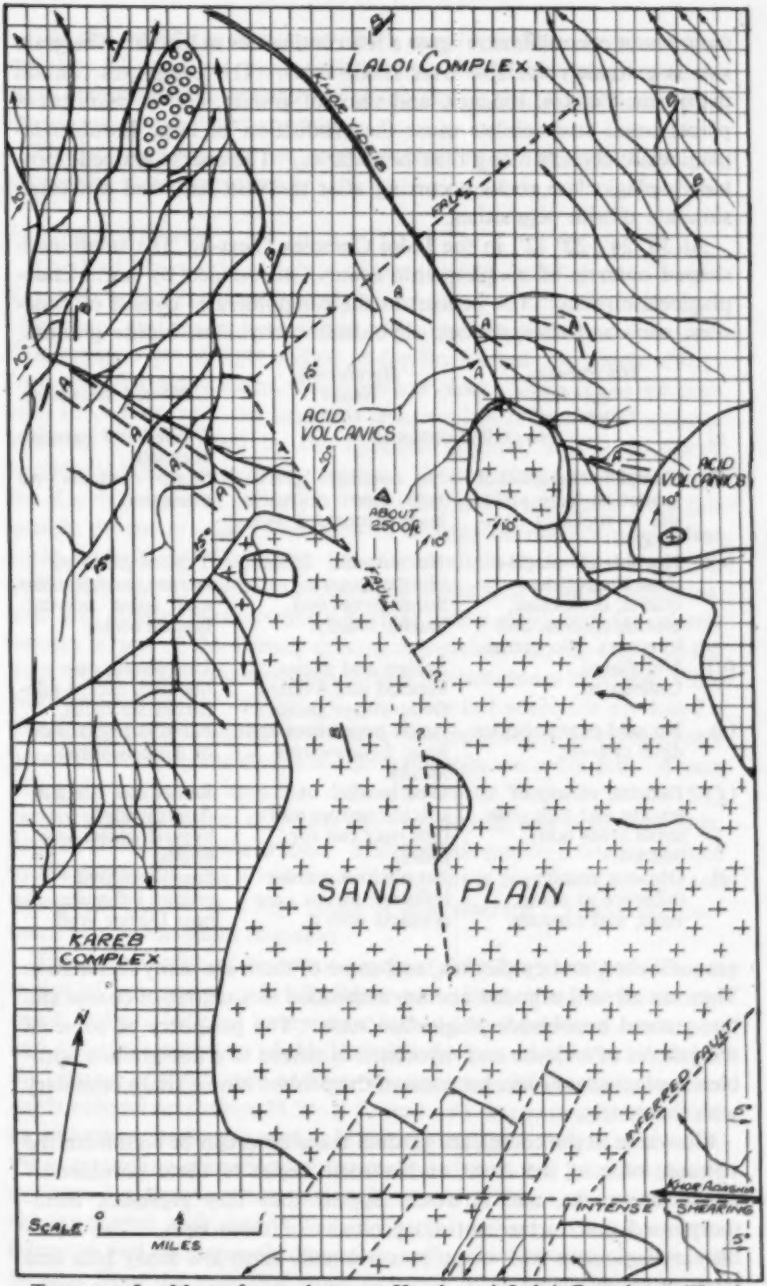
The position of the Awat Series in this proposed succession is fairly definite. At 36° 23′, 20° 22′ horizontal acid volcanics overlie the Nafirdeib Series which is striking E.–W., with a vertical dip. Near Jebel Talania, 36° 10′, 20° 56′, a magnificent volcanic neck is exposed ; it cuts through green andesitic beds of the Nafirdeib Series and is surrounded by acid volcanics dipping gently away from it. The neck is full of large blocks of flow-brecciated rhyo-dacites some up to ten feet in long diameter.

6. The Injection Granite

The injection granite seems to be in the form of a large batholith with the long axis aligned N.–S. It forms the highest hills, from Jebel Nakwat 5,774 feet, 36° 41′, 20° 04′, and Jebel Gumaderiba, 6,169 feet, through Jebel Oda, 7,412 feet, 36° 39′, 20° 20′, to Jebel Erba, 7,274 feet, 36° 50′, 20° 45′.

The injection granite is variable in colour from grey, white, and fawn to pink and red ; it is composed of quartz, orthoclase, oligoclase, green hornblende, and/or biotite. Normally it is a massive, medium-grained, well jointed rock and is often lineated near contacts. The contacts are unchilled and extremely irregular, the granite being highly injective into the country rock. Around 36° 35′, 20° 20′ an injection zone covers over forty square miles to the west of the main granite outcrop. Horizontal acid and intermediate volcanics of the Awat Series are cut by abundant veins and tongues of granite, and these latter often make up about one half of the area of the outcrops ; moreover, the Awat Series are commonly converted into hornblende-plagioclase rocks. The injection zone forms a marginal part of one of the large areas of hornblende-plagioclase rock-complexes in the centre of the map. The three main areas are the Nafirdeib, Laloi, and Kareb Complexes, and they cover some few hundred square miles.

The complexes are formed almost entirely of massive unfoliated, non-lineated rocks composed of hornblende and plagioclase. They may carry some quartz, orthoclase, epidote, and iron ore visible in hand specimen. Under thin section they are often found to be rich in apatite. Near contacts with the Red Granite, hypersthene, diopsidic augite, and biotite have been noted in thin section. The crystals of hornblende and plagioclase are randomly arranged and vary in size



TEXT-FIG. 5.—Map of area between Kareb and Laloi Complexes (Kareb Granite Centre 36° 25′ E., 20° 11′ N.); scale approx. 1 : 75,000 ; see Text-fig. 3 for legend.

from about one millimetre up to a few centimetres in length. The grain size is extremely variable over small areas. The complexes contain many small dykes, tongues, and veins of granite, and in numberless places small acid veinlets cause the production of large hornblende-plagioclase crystals along their boundaries. The coarse-grained hornblende-plagioclase rocks occurring after the vein had died out often simulate diorite pegmatites.

At 36° 24′, 20° 12′, in the Laloi Complex (Text-fig. 5) a small oval-shaped outcrop of conglomerate occurs, surrounded by hornblende-plagioclase rocks. The pebbles in the conglomerates consist of andesites, meta-andesites, dacites, rhyo-dacites, rhyolites, biotite granites,

	Hornblende-Plagioclase Complexes.	*Hornblende Schist and Gneiss.*	*Gabbroid Intrusions.*
a)	— No chilled contacts. —		Chilled and intrusive contacts.
b)	Complete and gradual gradation from andesite to rocks of complex.	No complete gradation from intrusive body to intruded rock.	Sharp contacts—no gradation.
(*c*)	Hornblende-plagioclase rocks (some quartz, orthoclase, biotite, epidote, and iron ore). No garnet.	Hornblende, felspar, biotite, quartz. Some garnet and marble locally.	Typical gabbros, norites, anorthosites and some talc-carbonate rocks.
(*d*)	Unfoliated. Unlineated.	Schists and gneiss lineated and foliated. Some augen gneiss.	Unfoliated, unlineated, except talc-carbonate rocks.
(*e*)	No acid pegmatites or dyke swarms.	Acids pegmatites and basic dyke swarms locally.	No acid pegmatites or dyke swarms.
(*f*)	Extreme variety of texture and type over small areas non-bedded.	Well bedded. A specific texture and type may run for miles.	Sometimes banded. Anorthosites, hypersthenites, ore bands.
(*g*)	Obvious granite influence as dykes, veins, and tongues.	No obvious granite influence except near contacts with it.	Small localized granite influence near Dirbat Well.

granodiorites, and epidiorites, and some of them are many feet across. They are all well rounded and are embedded in a matrix of coarse and fine-grained hornblende-plagioclase rock. The periphery of some of the pebbles of andesite and rhyodacite is altered to a fine-grained hornblende-plagioclase rock, but most of the pebbles have a sharp boundary with the matrix.

Elsewhere in the complexes gradual transitions can be seen from the volcanic beds of the Awat or Nafirdeib Series to these hornblende-plagioclase rocks, and it would appear that they represent metamorphosed and metasomatized products of these beds. The hornblende-plagioclase rock complexes normally form low stony hills and sand or gravel plains.

The distinguishing characters which suggest evidence for the differentiation of the three basic rock groups, the hornblende-plagioclase rock complexes, the hornblende schist and gneiss, and the gabbroid intrusions are tabulated opposite.

The Injection Granite has been seen cutting all the rocks described except the Basic Intrusives.

7. *The Red Granite*

The Red Granite is mainly a coarse-grained, unfoliated, and non-lineated, well jointed rock and is composed of quartz, orthoclase, oligoclase, and green hornblende with minor epidote and iron ore. The contacts are sharply chilled and often faulted. It nearly always forms low flat sandy plains, with a few low blocky hills. It has not been seen in contact with the Injection Granite, but it cuts the complexes believed to be formed by the Injection Granite, and so is placed tentatively higher up in the succession. In some places, such as around the Kareb Granite at 36° 26′, 20° 10′, veins and dykes traced from this granite do cause local production of coarser hornblende-plagioclase rocks in the Kareb Complex ; but on the whole the veins and granite dykes are not very common around any of the Red Granite intrusions, and any coarse hornblende-plagioclase rocks produced are merely coarser phases of the already existing complexes. At the south of the map the Omeiteb Granite is seen cutting the calcareous members of the Nafirdeib Series, 36° 25′, 19° 54′, and a contact aureole is produced a few hundred yards wide. Marbles, quartzites, biotite-diopside-quartz hornfels, and graphite-diopside-quartz hornfels are produced. A vein of quartz cutting a granophyre dyke near Dirbat Well, 36° 28′, 19° 54′, carries small quantities of galena and chalcopyrite and is thought to be derived directly from the granite. The Omeiteb granite is coarse-grained to the east and forms a low sandy plain, but it becomes finer-grained westwards and forms a high range of hills where it is frequently fractured in a north–south direction.

The eastern part of the coarse-grained Omeiteb granite encloses a wedge of paragneiss and calc-silicate-granulites ; these strike north–south and are believed to represent highly metamorphosed calcareous and quartzose members of the Nafirdeib Series. At 36° 29′, 19° 59′, at the contact of the granite and paragneiss, a vein of ilmenite some ten yards wide occurs striking N.W.–S.E., and near-by quartz veins brecciate an idocrase-schorlamite rock. Minor wollastonite occurs in some of the surrounding granulites. It is suggested that this provides strong evidence for showing that paragneiss represents part of a skarn area similar to that at Dirbat Well, that was formed originally by a norite intrusion and subsequently caught up in the Omeiteb Granite. It will be seen from the map that small outcrops of norite occur at 36° 34′,

20° 02′, and these are almost certainly associated with the norite at Dirbat Well, 36° 29′, 19° 55′ The ilmenite vein occurs about half way between these exposures.

8. *Acid and Basic Dykes and Sills*

The Red Granite is cut by a few dolerite dykes in places, but other minor intrusives cutting the Injection Granite, hornblende-plagioclase rock complexes and the Awat Series have not been seen cutting it, so that the age of these is still in doubt. These intrusions include quartz-porphyry and quartz-dolerite sills and dykes and grorudite dykes.

9. *Major Faulting*

The whole series of rock-groups outlined above have been affected by later faulting which, in places, seems to be of fault-block type. The southern part of Text-fig. 2 is a mosaic of tilted fault blocks with prominent escarpments and shallow dip slopes. The dry stream valleys (khors) reflect this pattern as they cross one fault block to the next and are either restricted into a gorge or open out into a plain. Unfortunately the topographical detail on the 1 : 250,000 Sudan Survey Map is too meagre to show this block mountain topography but it is clearly seen in the field and on the aerial photographs. The east to west contact marked F–F in the centre of the map may be a very large fault. Parts of it are definitely faulted, others are obscured by sand and gravel plains and yet other parts remain unvisited.

The larger khors often follow along the lines of the major faults, and fault breccias, intense local shearing and fracturing are often seen on their sides. Some of the fault breccias are over two hundred feet wide and it would appear that many of the faults are of tensional type.

Discussion

The succession of the Basement Complex of the Sudan north of latitude 6° N. was given by G. Andrew in 1948 (p. 95, *Agriculture in the Sudan*, Tothill), and is as follows :—

6. Soda-granites.
5. Unfoliated granites, etc.

B. Folding of non-metamorphic succession.

4. Unmetamorphosed greywackes and lavas (predominantly andesitic).

Folding and regional metamorphism (? A continued).

3. Plutonic intrusions : ultra basic rocks (serpentines, etc.), gabbro-norites, granodiorite, granite, all more or less foliated.

A. Folding and regional metamorphism.

2. Oldest plutonic orthogneisses.
1. Regionally metamorphosed paraschists, containing many slightly-metamorphosed bedded rocks, including lavas.

When presenting this scheme Andrew states " The only classification of this complex which is practicable is an arrangement according to a very rough and arbitrary scale of metamorphism ".

It is clear that in general this succession is in close agreement with the one I have presented. The main differences are that I have found the newer volcanics, my " Awat Series " and Andrew's division 4, to be predominantly rhyo-dacitic with only subordinate andesites. Also I have given reasons for a division of the older sedimentary, volcanic, and paraschitic rocks into two groups, one pre- and one post- the " oldest plutonic orthogneiss " ; in Andrew's division 2, however, if one wished to conform with Mr. Andrew's scheme then one would have to argue as follows :—

(*a*) The rocks of the Nafirdeib Series have been intruded and regionally metamorphosed by a plutonic orthogneiss in a large tectogene and have been converted into three great regional zones of different metamorphic grade forming concentric rings around the orthogneiss.

(*b*) These zones of different grade are produced as follows :—

i. Basic lavas and greywackes.	Nafirdeib Series as described. Very low grade.	Intermediate lavas and greywackes.
ii. Chlorite albite schists. ± talc, tremolite, epidote.	Low grade	Calcite, chlorite schists ± sericite and epidote.
iii. Plagioclase hornblende schists ± garnet	High grade	Biotite hornblende schists.

(*c*) The high grade metamorphic products are hornblende-plagioclase schists with or without biotite and garnet. These would correspond with the " hornblende schists and gneiss " of my succession and a glance at the north of Text-fig. 2 shows that they form a partial inner ring around the " Acid gneiss ".

(*d*) The low grade metamorphic products are calcareous and chloritic schists with or without talc, tremolite, albite, and epidote, and would correspond to the " Schists and Slates " of my succession. They occur between the hornblende schists and gneiss and the Nafirdeib Series. The Nafirdeib Series composed of meta-volcanics and meta-greywackes, with a strong development of epidote and chlorite, then represent the outermost limits of the tectogene.

This scheme is very suggestive and is one of the alternative possibilities that will have to be considered when further work is done. For the moment there is not sufficient field or microscopic evidence to decide in favour of any one interpretation.

Conclusion

The succession as presented is best summarized in the form of a table as follows :—

The three-fold sedimentary and volcanic succession

Awat Series

——— proved unconformity

Nafirdeib Series

——— unconformity?

Primitive System { Schists and slates / Hornblende schists and gneiss

is satisfactory for most of the Northern Red Sea Hills and the upper unconformity is considered proven. Each of these three great groups outcrop over very large areas in the Red Sea Hills, and indeed over the North-Eastern Sudan ; however, the succession given here is only valid at present for the area described. In other areas of the Red Sea Hills, particularly to the south of the area described, the rock-groups have not yet been delimited satisfactorily and they include members which have no obvious equivalents to the north.

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Shear-Folding in the Mylor Slates, near Porthleven, Cornwall

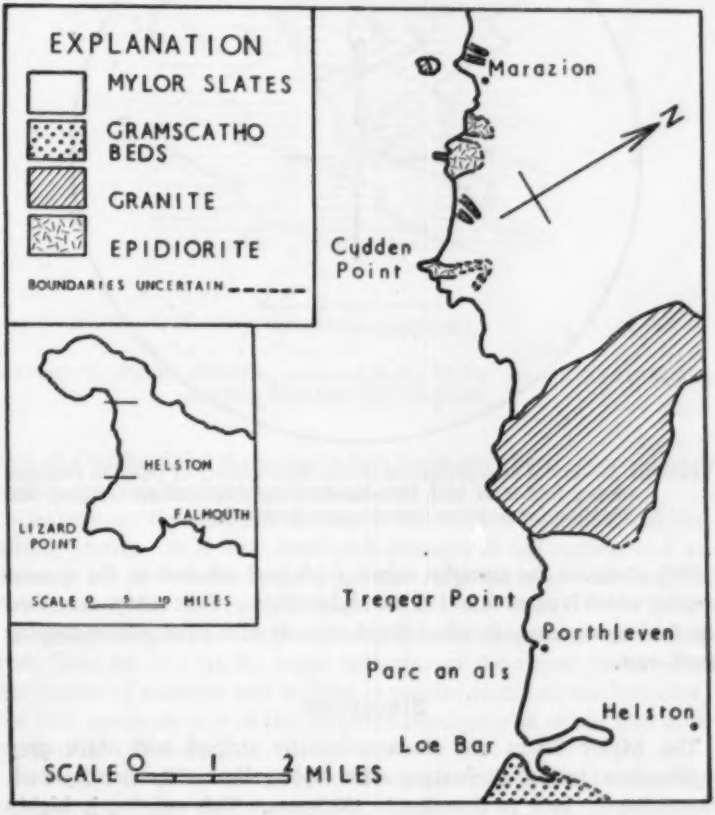
By M. Stone and J. L. M. Lambert

Abstract

Recumbent shear folds and their related structures in the Mylor Slates are briefly described. It is concluded that folding has been produced by subhorizontal shearing stresses acting in a north-westerly or south-easterly direction.

Introduction

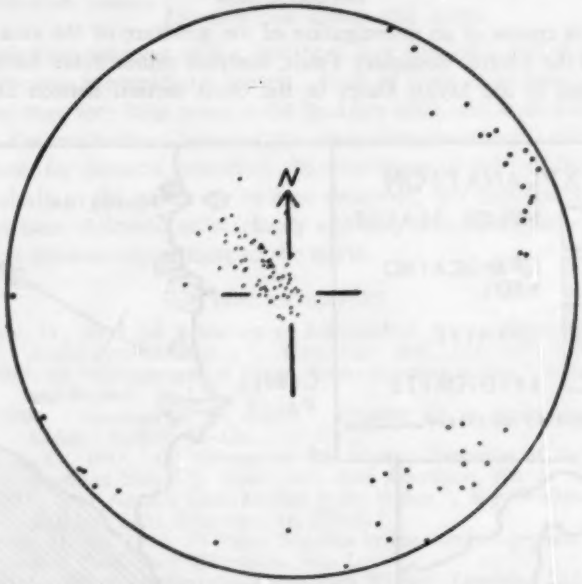
IN the course of an investigation of the structure of the area north of the Lizard Boundary Fault, complex minor folds have been examined in the Mylor Slates in the coast section betwen Loe Bar



Text-fig. 1.—Location map.

and Marazion (Text-fig. 1). This examination revealed structural features not hitherto recorded from this region.

Previous workers in this area were more concerned with the lithological features and the age of the Mylor Slates than with detailed structures. However, Hill (1913) describing recrystallization in the slate near the Godolphin granite, referred to ". . . . shear planes that impart the structure of a schist . . .". He also noted the marked contortion of the bedding in the coast section immediately north-west of Tregear Point and on the northern side of Parc-an-als cliff. Hall



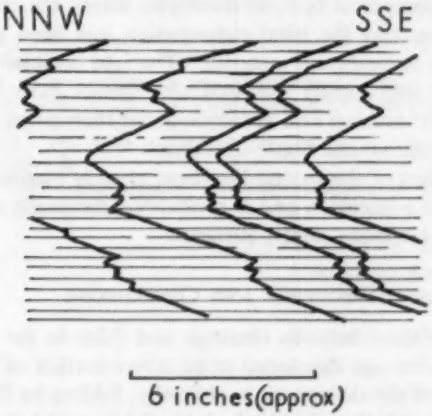
TEXT-FIG. 2.—Equal-area projection (lower hemisphere) of poles to cleavage (dots), fold axes and cleavage-bedding intersections (circles) and lineation (crenulation) on cleavage (crosses).

(1930) observed the complex minor folds and referred to the quartz-veining which is often found in the Mylor Slates. Flett (1946) described the folding as nearly isoclinal (hypisoclinal) with axial planes dipping south-east.

STRUCTURES

The Mylor Slates are characteristically striped with dark grey argillaceous bands alternating with light-yellow silty bands, each measuring $\frac{1}{16}$ inch to 2 inches in thickness. This striping is highly folded and often discontinuous.

The most striking feature of the Mylor Slates is this intense minor recumbent folding. The fold axes plunge dominantly north-east and the apical planes have a gentle regional dip to the south-east (Text-fig. 2). In profile the folds have apparently thickened apical regions and attenuated limbs, but the " thickness " of a stratum measured parallel to the apical plane is usually fairly constant. This " similar " folding is shown in Text-fig. 3, which illustrates the general scale of the minor folding. However, wavelengths vary from less than an inch to several feet. Amplitude, also, is variable, but the amplitude/wavelength ratio appears to bear a distinct relation to the true thickness of the limbs. At Tregear Point and at several localities north-north-



TEXT-FIG. 3.—Profile of folding observed in the Mylor Slates : diagrammatic drawing based on field sketches.

west of Cudden Point the strata in fold limbs have been stretched and broken, forming discontinuous bands and fold breccias.

Cleavage in the slates takes the form of closely spaced definite parting planes. It is well developed throughout the section and in places it has been intensified by mimetic crystallization of mica, so that the rock has become phyllitic.

Cleavage is parallel to the apical planes of the minor recumbent folds (Text-fig. 3) ; its dip varies with that of the apical plane. The intersection of cleavage and bedding is parallel to the minor fold axes. The field measurements of this lineation together with minor fold axes are shown in Text-fig. 2.

A second lineation lies approximately at right angles to the fold axes and parallel to the cleavage dip. It appears as a fine crenulation on the cleavage surfaces.

Shear Folding

Shear folding is produced by unequal slip on closely spaced surfaces (cleavage or schistosity) that are inclined to the bedding. The bedding on one side of a slip surface will be offset relative to the bedding on the other side.

In the Mylor Slates variable offset of bedding and quartz-veins parallel to the cleavage has been observed at numerous localities between Marazion and Loe Bar. Although this is regarded as definite evidence for shear-folding, it can also be produced in the incompetent beds of flexural-slip folds [for example, see Hills (1945)]. However, whereas deformation in flexural slip folds is largely controlled by flexure of the competent beds, in the Mylor Slates, the competent beds are subordinate and the total deformation has been controlled by shearing in the incompetent material. The fold breccias in the Mylor Slates indicate that locally the thin silty bands have behaved in a more competent fashion and accommodated themselves to the movement by attenuation and finally fracture.

The orientation of the second lineation, already mentioned, suggests that it is a true a-lineation and is probably structurally related to the lineation seen on many thrust surfaces.

Discussion and Conclusions

The close relation between cleavage and folds in the Mylor Slates indicates that cleavage developed as an active surface of movement at an early stage of the deformation. Initially, folding by flexure or flow may have occurred, though, if it had, the folds must have attained the geometry of similar folds before cleavage developed. While this is possible in flexure folds in incompetent strata, it is unlikely that flow folds could have maintained a parallelism of apical planes and a constant " thickness " of bedding parallel to these planes. If flexure had occurred initially, it must have given way to shear folding very soon after movement commenced, otherwise the early formed cleavage would have been rotated by continued flexure to form cleavage fans.

Therefore, it is concluded that the Mylor Slates in this section have yielded to the deforming stresses by slip along closely spaced subhorizontal cleavage surfaces to produce minor recumbent shear folds.

Direct unilateral compression may have initiated the tectonic conditions for shear folding. However, since this type of folding requires no crustal shortening, compression can be discarded as the immediate cause. Since the folds are recumbent, and in the absence of evidence to suggest regional tilting after folding, the most probable explanation is that a shearing couple must have acted subparallel to the earth's surface in a north-westerly or south-easterly direction.

This would suggest either that shear has been produced by an over-riding or under-riding rock mass, or that it has developed during movement under the influence of gravity. In either case it seems probable that soon after the rock mass began to move slip planes developed due to frictional drag and these became the loci of all further movement, thus producing recumbent similar folds.

ACKNOWLEDGMENT

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Holothurian Spicules from the Oxford Clay of Redcliff, near Weymouth (Dorset)

By Frank Hodson, Barbara Harris, and Louise Lawson

Abstract

Nine species (eight new) of holothurian spicules are recorded from the Oxford Clay (*cordatum* zone) of Redcliff, near Weymouth on the Dorset coast. The new species are described and named and the significance of a close association of *Rhabdotites* and *Theelia* is discussed. Previous records of holothurian spicules from British strata are reviewed.

Introduction

HOLOTHURIAN spicules are not commonly recorded from British strata. The earliest records are due to C. Moore (1872, p. 117), who wrote of four species of holothurian spicules from the Liassic and Inferior Oolite beds. Although he named the Inferior Oolite example, *Chirodota carpenteri*, he does not seem to have adequately described or figured it. So far as we know, the material on which it was based is no longer available; it is not in the Charles Moore collection, which is at present housed in Bristol Museum.

R. Etheridge, Jr. (1873, p. 98), reported the discovery by J. Bennie of holothurian spicules in the shales of the Carboniferous Limestone Series of Scotland; and described the spicules in an important paper eight years later (Etheridge, 1881). They consisted of hooks, wheels, perforated plates, and other less easily classifiable bodies. The hooks were found in close association with the perforated plates, and it seems likely that they belonged to the same species of holothurian. This creature was assigned (p. 194) to a new genus *Achistrum*. Peach (1900, p. 223) cited some of these forms from the Carboniferous of Fife.

Since 1932 the kinds of spicules figured by Etheridge have been distributed among various minor taxonomic units. In spite of the probability that the hooks and perforated plates belonged to the same animal species, a proposal that the name *Achistrum* should be restricted to the hook-like forms, has been made (Croneis and McCormack, 1932, p. 142), and the perforated plates have been assigned to *Eocaudina mccormacki* Frizzell & Exline (Frizzell and Exline, 1955, p. 87).

Blake (in Tate and Blake, 1876, p. 443 and pl. 17, figs. 42 and 43) reported holothuroid spines or hooklets from the Lower Lias of Yorkshire; and his fig. 43 clearly depicts a form of *Achistrum*. Further, fig. 45 of Tate and Blake's plate 17, though one of the Liassic forms that they described (p. 448) as doubtfully crinoid, is a perforated plate that may well be holothurian. In this work occurs the first mention, so far as we have been able to find, of a feature of one of

the groups of fish-hook-like spicules—namely the occurrence of a " cross bar " or thread of spicular substance which crosses the " eye ". Although the cross bar is mentioned in the text, the illustration does not show it.

Whidborne (1883, p. 537) described two species of wheel-like spicules from the Inferior Oolite of Burton Bradstock. These are now known as *Theelia convexa* (Whid.) and *Hemisphaeranthos gracillima* (Whid.). Woodward (1893, p. 370) recorded " *Chirodota* " from the Lias of Somerset, Northamptonshire and Yorkshire.

Bell (1897, p. 12) recorded *Cucumaria dubiosa* Herdm. from the Pliocene clays of St. Erth, and *Psolus phantopus* L. from the Pleistocene clays of various localities. Later (Bell, 1921, p. 16) he gave the same record in almost the same form, except that the words " Pliocene clays " were omitted from the record of *Cucumaria* from St. Erth.

J. Smith (1901, p. 509) recorded four of Etheridge's species of Holothuroidea from the Carboniferous Limestone in the Clyde Drainage area of Scotland and *Psolus phantopus* L. from " post drift " deposits of the same area (Smith, J., Scott, T., and Steel, J., 1901).

Upton (1917, pp. 115–17, recorded spicules which would now be referred to *Theelia* from the Inferior Oolite and Lias of Gloucestershire, Dorset and Somerset, and mentioned a specimen found by him in the Upper Chalk of Purley, Surrey.

Henderson (1935, p. 554) recorded holothurian plates and spicules from the Lower Lias of Hock Cliff, Fretherne, but did not identify the specimens further.

Davies (1936, p. 340) compared specimens isolated from the London Clay of Sheppey with spicules of the Recent species *Trochostoma* (*Molpadia*) *violacea* Studer and noted that other types had been collected from the same beds elsewhere.

Of particular interest is a paper by Deflandre-Rigaud (1946) in which Oxfordian holothurian spicules from Villers-sur-Mer, some 120 miles to the south-east across the English Channel were described.

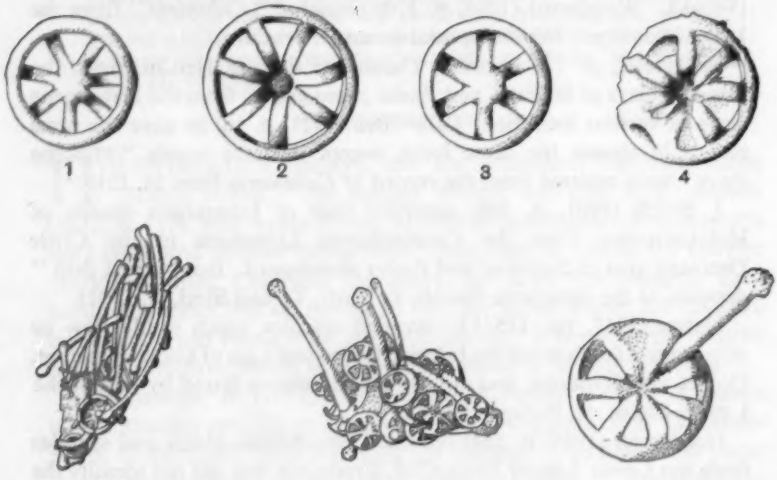
Materials, Horizon and Locality

All the specimens that form the main subject of this paper were collected by us from the coastal section in the Oxford Clay (*cordatum* zone) at Redcliff, 3 miles north-east of Weymouth, Dorset (National Grid reference 30/712817). Holothurian remains were distributed throughout the whole of the 50 feet or so of the beds exposed, except for the top few feet just below the junction with the Corallian. These latter beds were much more arenaceous. Specimens were not uncommon in the cleaned residues from the clays and, having regard to the delicate nature of the fossils, their state of preservation was excellent. The aggregation of " wheels " and " hooks ", and their

adhesion in spite of washing and sieving of the matrix, was particularly fortunate.

The figured material, which is a selection from the whole, has been presented to the Sedgwick Museum, Cambridge, and the numbers prefixed with " J " are the registration numbers of the specimens in that museum.

We are indebted to Mr. L. Bairstow, of the British Museum (Natural History), for help and constructive criticism and to Mr. A. G. Brighton, of the Sedgwick Museum, Cambridge, for the loan of Whidmore's figured material.



TEXT-FIGS. 1–7.

FIG. 1.—*Theelia wessexensis* sp. nov. Upper surface of holotype. J. 35776. × 87.
FIG. 2.—Ditto. J. 35777. Lower surface. × 104.
FIG. 3.—*Theelia wessexensis* var. J. 35778. × 92.
FIG. 4.—*Theelia convexa* (Whidborne). Holotype. J. 3741. × 82.
FIG. 5.—Association of *Theelia wessexensis* sp. nov. and *Rhabdotites dorsetensis* sp. nov. J. 35779. × 41.
FIG. 6.—Ditto. J. 35780. × 49.
FIG. 7.—Ditto. J. 35781. × 88.

The numbers preceded by " J " are the registration numbers of the specimens presented to the Sedgwick Museum, Cambridge.

SYSTEMATIC DESCRIPTIONS

FAMILY.—THEELIIDAE Frizzel & Exline 1955.

GENUS.—THEELIA Schlumberger 1890.

Theelia wessexensis sp. nov. Text-figs. 1, 2, 5–7, 17.

Holotype : J. 35776, Text-fig. 1.

Description : Calcareous, concavo-convex, rotiform spicules ; each with seven, symmetrically disposed, strap-like spokes, which are arched and are attached to the lower margin of a vertical or slightly inwardly-inclined rim. Outline in plan circular to barely heptagonal. Central hub not ornamented on the lower flat surface but sometimes pustulate on the upper, boss-like, convex surface. Free margin of the rim not crenulate.

Dimensions: Diameter : 140–150–160–170–180–190–200–210–220μ
Frequency : 1 0 1 2 7 2 4 2

Discussion: This form is near to *T. convexa* (Whidbourne) from the Inferior Oolite ; the figured holotype of which is in the Sedgwick Museum, Cambridge (J. 3741). This holotype is re-figured here (Text-fig. 4) but its poor preservation precludes exact comparison with our material. One obvious difference, however, concerns the size, since the holotype of *T. convexa* has a diameter of 250μ which is greater than and outside the range of variation of that of *T. wessexensis*.

A single example of a six-spoked *Theelia* was found in the material from Redcliff (Text-fig. 3). Apart from the fewer spokes, it had the characters of the specimens we have referred to *T. wessexensis*, and the paucity of material does not warrant a new name.

FAMILY.—ACHISTRIDAE Frizzel & Exline 1955.

GENUS.—ACHISTRUM Etheridge 1881, emend. Frizzel & Exline 1955.

Species referrable to this genus fall into three groups as follows :

GROUP I.—Terminal loop empty.

A. nicholsoni Etheridge	Carboniferous.
A. brownwoodensis (Croneis)	Carb.—Permian.
A. ludvigi (Croneis)	Carboniferous
A. permianum (Spandel)	Permian (Zechstein)
A. triassicum Frizzel & Exline	Trias.
A. issleri (Croneis)	Lias and Oxfordian
A. bathonianum Frizzel & Exline	Bathonian.

GROUP II.—Terminal loop occupied by two thorn-like processes.

A. bartensteini Frizzel & Exline	Lias.

GROUP III.—Terminal loop with a cross-bar.

A. gamma sp. nov.	Oxfordian.
A. monochordata sp. nov.	Oxfordian.
A. sp. (Tate & Blake, 1876, p. 443)	Lias.

Examples of Groups I and III are found in the Redcliff material.

A. cf. *issleri* (Croneis) Text-figs. 8 and 9.

We compare certain examples of *Achistrum* in our material in which the terminal loop is empty to this continental Liassic species named by Croneis (Croneis and McCormack, 1932, p. 144).

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TEXT-FIGS. 8–13.

FIG. 8.—*Achistrum* cf. *issleri* (Croneis). J. 35782. × 48.
FIG. 9.—Ditto. J. 35783. × 41.
FIG. 10.—*Achistrum monochordata* sp. nov. var. J. 35784. × 39.
FIG. 11.—*Achistrum monochordata* sp. nov. Holotype. J. 35785. × 31.
FIG. 12.—*Achistrum gamma* sp. nov. var. J. 35786. × 62.
FIG. 13.—*Achistrum gamma* sp. nov. Holotype. J. 35787. × 48.

The numbers preceded by " J " are the registration numbers of the specimens presented to the Sedgwick Museum, Cambridge.

A. gamma sp. nov. Text-figs. 12–13.

Holotype : J. 35787, Text-fig. 13.

Description : *Achistrum* with a cross bar in the terminal loop which in typical specimens is markedly bifurcate (Text-fig. 13) ; and in certain others the bifurcation is only incipient (Text-fig. 12).

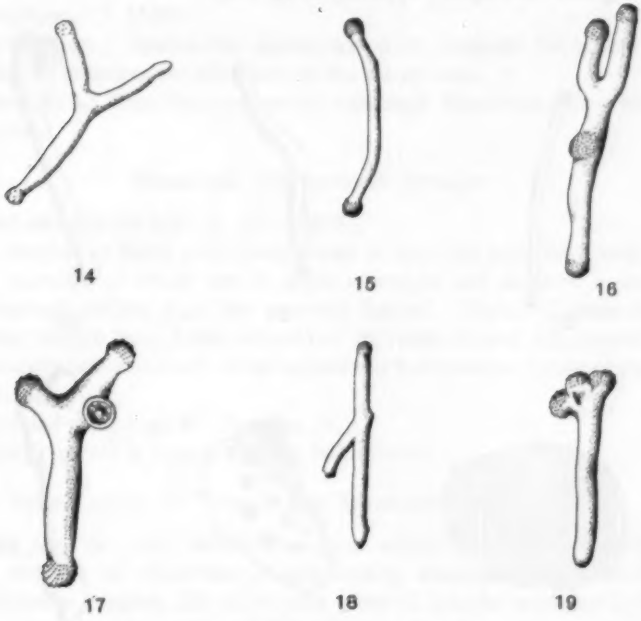
A. monochordata sp. nov. Text-figs. 10–11.

Holotype : J. 35785, Text-fig. 11.

Description : *Achistrum* with a cross-bar typically approximately centrally placed within the terminal loop. The position of the cross-

bar is very variable and in some specimens it is laterally displaced and may be almost fused with the eye-rim (Text-fig. 10).

FAMILY.—STICHOPITIDAE Frizzel & Exline 1955.
GENUS.—RHABDOTITES Deflandre-Rigaud 1952.



TEXT-FIGS. 14–19.

FIG. 14.—*Rhabdotites divergens* sp. nov. Holotype. J. 35788. × 57.
FIG. 15.—*Rhabdotites dorsetensis* sp. nov. J. 35789. × 45.
FIG. 16.—*Rhabdotites bifidus* sp. nov. Holotype. J. 35790. × 45.
FIG. 17.—*Rhabdotites divergens* sp. nov. with small *Theelia* sp. fused to shaft. J. 35791. × 73.
FIG. 18.—*Rhabdotites* cf. *divergens* sp. nov. J. 35792. × 37.
FIG. 19.—*Rhabdotites tridens* sp. nov. Holotype. J. 35793. × 39.

The numbers preceded by " J " are the registration numbers of the specimens presented to the Sedgwick Museum, Cambridge.

Rhabdotites dorsetensis sp. nov. Text-figs. 5, 15, 20–21.

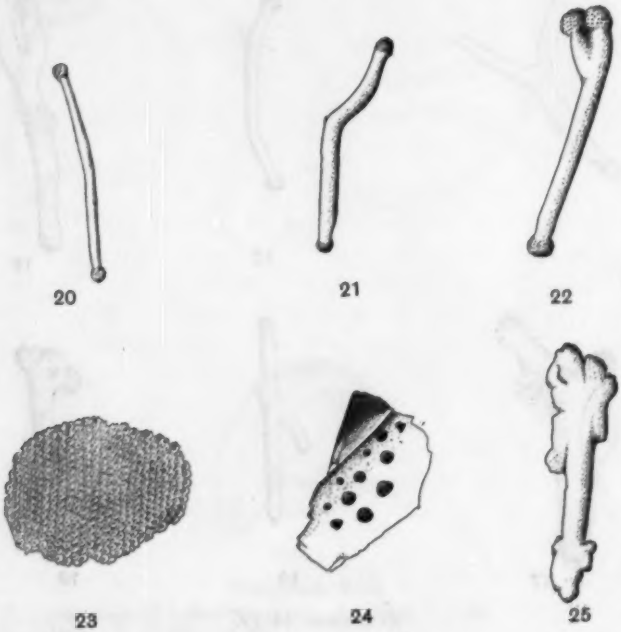
Holotype : J. 35794, Text-fig. 20.

Description : Slender rods, typically 600–700μ in length and 10 to 20 times as long as broad. Typically gently arcuate (Text-figs. 4 and 20) but some examples (Text-figs. 15 and 21) have angular flexures at one or more points along their lengths. Ends swollen with pustules in linear series.

Rhabdotites divergens sp. nov. Text-figs. 14, 17, and 18.

Holotype : J. 35788, Text-fig. 14.

Description : *Rhabdotites* characterized by a lateral branch that diverges from the parent branch and maintains the angle of divergence throughout its length. Typically 500μ long.



TEXT-FIGS. 20–25.

FIG. 20.—*Rhabdotites dorsetensis* sp. nov. Holotype. J. 35794. × 48.
FIG. 21.—Ditto. J. 35795. × 42.
FIG. 22.—*Rhabdotites bifidus* sp. nov. J. 35796. × 57.
FIG. 23.—Perforated plate type A. J. 35797. × 40.
FIG. 24.—Perforated plate type B. J. 35798. × 47.
FIG. 25.—*Rhabdotites irregularis* sp. nov. Holotype. J. 35799. × 32.

The numbers preceded by " J " are the registration numbers of the specimens presented to the Sedgwick Museum, Cambridge.

Rhabdotites bifidus sp. nov. Text-figs. 16 and 22.

Holotype : J. 35790, Text-fig. 16.

Description : *Rhabdotites* with the shape of a tuning-fork by virtue of a branch which, immediately after bifurcation, bends back into a line parallel with the parent branch.

Rhabdotites tridens sp. nov. Text-fig. 19.

Holotype : J. 35793.

Description : *Rhabdotites* characterized by trifid terminal branching.

Rhabdotites irregularis sp. nov. Text-fig. 25.

Holotype : J. 35799.

Description : *Rhabdotites* characterized by irregular branching in which the branches remain fused to the parent rod.

Previous to these descriptions no branched *Rhabdotites* have been reported.

Doubtful Holothurian Remains

Perforated plate type A. Text-fig. 23.

A number of finely perforated plates of this type have been seen in our material, of which one is more complete and displays a more pentagonal outline than the example figured. Plates of somewhat similar texture have been referred to *Etheridgella* and *Mortensenites* but we are not convinced of the undoubted holothurian nature of these specimens.

Perforated plate type B. Text-fig. 24.

This fragment is only doubtfully holothurian.

The Relationship of Theelia and Rhabdotites

The fact that our material contains certain specimens (Text-figs. 5–7 and 17) of wheel-like *Theelia* closely associated with rod-like *Rhabdotites* suggests that these two types of spicule belonged to the same animal. Mortensen (1937, p. 22) has already commented on the affinity of the rods now referred to *Rhabdotites*. He claimed that the large spicules, figured in his pl. iii, figs. 4 & 5, so strikingly recall those of *Chirodota stuhlmanni* Lampert figured by S. G. Heding, 1931, p. 677, fig. 12. 6, that there can scarcely be any doubt that they too must belong to the genus *Chirodota*, to which Mortensen referred also the fossil wheels of his own pl. iv, figs. 1 and 2. These fossil wheels would now be assigned to *Theelia*. Hitherto, however, no actual close association of *Rhabdotites* and *Theelia* in the fossil state has been recorded.

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DEPARTMENT OF GEOLOGY,
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Conjugate fold systems in the Moine Thrust Zone in the Lochcarron and Coulin Forest areas of Wester Ross

By M. R. W. Johnson

Abstract

The Moine Thrust Zone in the Lochcarron and Coulin Forest areas contains numerous small scale folds which plunge eastwards. The axial planes of these folds are inclined towards the north or south so that no regional directional translation of the rocks can be postulated from these structures, whose symmetry as a whole is orthorhombic. The folds are considered to have resulted from local lateral extension and concomitant compression of laminated rocks involved in the thrusting.

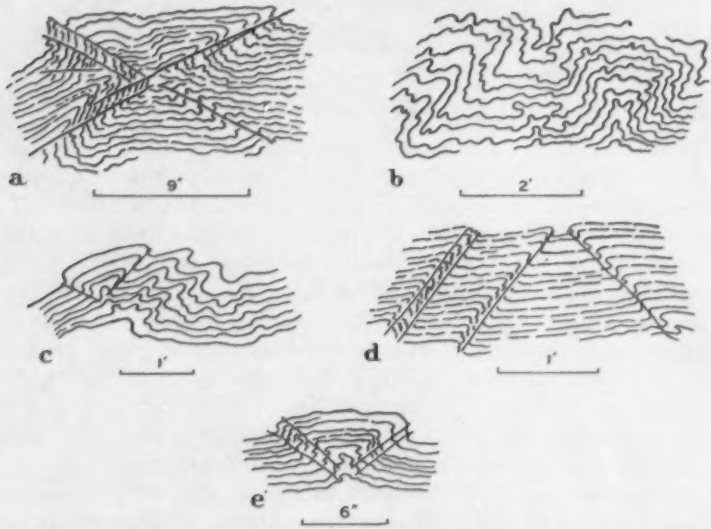
Introduction

THE Lochcarron and Coulin Forest areas of Wester Ross include parts of the Kishorn and Moine Nappes of the Caledonian thrust zone of the North-West Highlands of Scotland (see Bailey 1950, fig. 4, p. 234). During a recent investigation of the tectonics of the Moine Thrust Zone in these areas it was noted that several of the folds in the deformed Torridonian, Lewisian, and Moine rocks have an unusual tectonic style. These "Conjugate Fold Systems" appear to be confined to the Thrust Zone within the areas mapped. The geometry and kinematics of these folds and their relationship to the Moine Thrust movements are described and discussed in the present paper. A more complete account of the tectonic phenomena associated with the Moine Thrust movements will be given in a later paper.

The tectonic pattern of the thrust zone is dominated by a strongly developed lineation which, plunging at a low angle towards the east or east-south-east, is shared by the Torridonian, Lewisian, and Moine rocks in the areas examined : on all scales from the thin section to the geological map a strong penetrative movement operated about this lineation during the main phase of transport on the Moine Thrust. At Lochcarron the lineation occurs in the inverted Torridonian of the great Loch Alsh fold, the deformed Lewisian, and the Moine ; at Coulin it extends for roughly two miles east of the Moine Thrust outcrop where it gives place to a different structural pattern in the psammitic schists.

Folds varying in wavelength from 1–200 feet have axes parallel to the E.-W. or ESE.-WNW. lineation ; they may post-date the lineation though the structures are genetically related. The eastward plunging folds (referred to as the E.–W. folds) are usually symmetrical and asymmetrical monoclinic folds ; the middle limb of an overturned fold is sometimes cut by one or two shear planes which dip parallel to the axial planes. Individual monoclinic folds indicate movement perpendicular

to the fold axis during the phase of deformation that produced the folding. On a regional scale axial planes of the E.–W. folds in the thrust zone have no preferred orientation ; they may dip north and south in adjacent folds within a single exposure. Clearly no consistent sense of translation of upper beds relative to lower can be deduced from the folds which, considered as a whole, have orthorhombic symmetry. Folds with single axial planes cannot be considered individually ; they form part of a fold system in which the inclinations



TEXT-FIG. 1.—Profiles of Conjugate Fold Systems in the Moine Thrust Zone of the Lochcarron and Coulin Forest areas of Wester Ross. The folds plunge at gentle angles towards the east or east-south-east : profiles were drawn from *ac*-joint faces, looking down the plunges of the fold axes.

Examples (a) and (b) occur in Lewisian mylonite at Lochcarron ; example (c) occurs in the Moine at Coulin ; (d) and (e) occur in the inverted Torridonian at Lochcarron.

of axial planes are opposed. Such a fold system is termed by the writer a " Conjugate Fold System ". These constitute a special case of Greenly's polyclinal type of folding (see Greenly, 1919, pp. 190–1). Small scale conjugate fold systems appear to be scattered throughout the thrust zone.

GEOMETRY AND KINEMATICS OF CONJUGATE FOLD SYSTEMS

Profiles of conjugate fold systems are illustrated in Text-fig. 1 : a–d are complete systems, d–e are partially developed systems. The

scale is important : the conjugate folds are usually about 1–3 feet across. The tectonic style suggests brittle deformation.

The fold systems consist of paired reversed folds that are controlled by a pair of symmetrically arranged slip planes which are inclined towards one another and intersect parallel to the eastward plunging fold axes. The slip planes are parallel to the axial planes of the reversed folds and cut the median limbs of the folds. Occasionally late stage brecciation of the mylonites occurs along the slip planes.

Some conjugate fold systems have formed from monoclinal steps in the parting planes which evolve into overturned *Z*-folds ; later two shear planes developed at the fold hinges (Text-fig. 1a). Conjugate folds have also developed without shear planes (see Text-fig. 1b).

The geometry of the conjugate fold systems indicates that they cannot have been produced by a simple shear couple operating perpendicular to the fold axis. The folds have near orthorhombic symmetry : they possess two planes of symmetry which are normal to two of the three symmetry axes (see Text-fig. 2A).

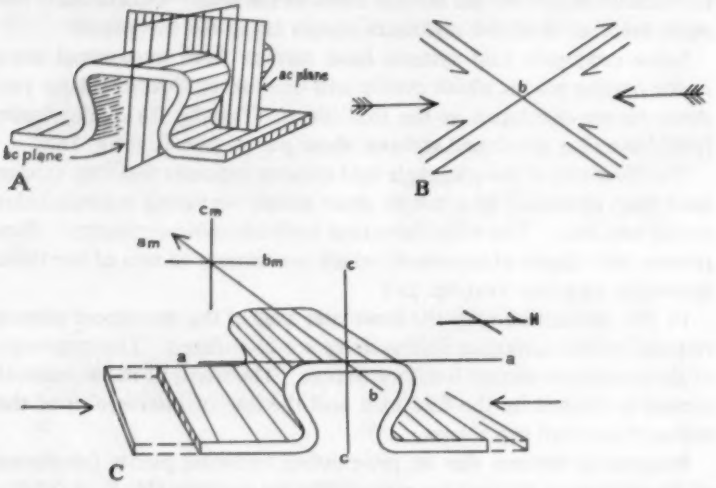
In this description only the kinematic axes of the movement picture responsible for conjugate fold systems are considered. The symmetry of the movement picture is orthorhombic. The *b*-axis of the movement picture is defined by the fold axes and the line of intersection of the mutually inclined slip planes.

Penetrative flexural slip on pre-existing mylonite planes (*ab*-planes of the movement picture) has operated in the *ac*-plane (N.–S. or NNE–SSW direction) with consequent shortening of the rock mass perpendicular to the fold axis. Later, the movements have been concentrated along the discrete intersecting slip surfaces : flexural slip on *ab* ceased at this stage in the deformation. On the scale considered the rock mass has been unevenly squeezed and confined : shear couples have not operated. The geographical orientation of the kinematic axes is illustrated in Text-fig. 2C.

Relationship of Folds to the Moine Thrust

The preceding account has been confined to the orthorhombic conjugate fold systems which make up a small proportion of the E.–W. folds in the thrust zone. The dominance of monoclinic *Z* or *L* folds seems to suggest that the overall movement picture responsible for the E.–W. folds was monoclinic : conjugate fold systems would therefore merely represent local modifications of the overall picture. On this hypothesis the folds resulted from monoclinic deforming movements operating in the *ac*-plane (N.–S. approximately), indicating a transport of upper beds northwards or southwards relative to the lower. Clearly such monoclinic movements would be produced by discontinuous transport along the Moine Thrust northwards or southwards

depending on the dominant direction of overturning of the folds. However, this hypothesis cannot be applied to the structures under discussion because on a regional scale the monoclinic folds are not consistently overturned in a single direction ; about 60 per cent of their axial planes dip southwards or are vertical and 40 per cent dip northwards. It is tentatively suggested, therefore, that on a regional scale the symmetry



TEXT-FIG. 2.—Kinematic interpretation of the Conjugate Fold Systems (orthorhombic folds).

2A illustrates the ideal orthorhombic symmetry of the folds : two planes of symmetry, the *ac* and *bc* planes of the fabric, are normal to two of the three fabric axes.

2B shows the sense of movement along the slip planes which occur in some Conjugate Fold Systems. The maximum compressive stress producing the slip movements is shown by arrows with barbs.

2C illustrates the spatial relationship between the movements which produced the Conjugate Folds (*a*, *b*, *c*) and the major tectonic transport westward on the Moine Thrust (a_m, b_m, c_m). The relationship is considered to be applicable to all E.-W. folds in the thrust zone.

of the movement picture responsible for all styles of E.–W. folds in the thrust zone is orthorhombic. Clearly, unrestricted transport on the Moine Thrust perpendicular to these fold-axes is impossible.

This present analysis suggests that the E.–W. fold axes are roughly parallel to the direction of tectonic transport on the Moine Thrust (Peach & Horne 1907). Folds whose axes are parallel to the direction of transport have been termed *a*-folds by previous workers, e.g. Cloos (1946), Strand (1944), and Balk (1952). Consideration of the fold geometry indicates that the maximum compressive stress responsible

for the folds in the Moine Thrust Zone operated perpendicular to the fold axes, in a roughly north-south direction. The decrease in cross sectional area normal to the fold axes was accompanied by extension of the rock mass parallel to them and to the axis of minimum confining pressure. The orthorhombic fold pattern in the thrust zone reflects orthorhombic deforming movements, implying restricted transport (Fairbairn, 1949, p. 215) of the rock mass perpendicular to the fold-axes. The relationship in time and place between the orthorhombic movements responsible for the E.–W. folds and the dominantly discontinuous monoclinic transport westwards along the Moine Thrust is problematical. Text-fig. 2c illustrates diagrammatically the geographical relationship between the kinematic axes of the folds (a, b, c) and the presumed kinematic axes of the regional transport on the Moine Thrust (a_m, b_m, c_m). The spatial relationships are as follows :—

	N.–S.	E.–W.	Vertical
Kinematic axes of folds	a	b	c
Kinematic axes of major transport . . .	b_m	a_m	c_m

The E.–W. folds are accommodation structures produced by complementary stresses within the thrust zone during westward transport along the Moine Thrust : the folds do not reflect the direction of forces applied externally to the rock mass as a whole. Thus the rocks have undergone solid flow perpendicular to the main direction of transport, with the formation of narrow belts of complementary E.–W. folding in zones of tectonic thickening in the thrust slices. The symmetry of these deforming movements is ideally orthorhombic : lateral extension of the westward moving rock masses occurred under strong vertical confinement during the rolling process. Extension would be greatest wherever the moving rock mass encountered resistance to forward movement with consequent restriction of axial flow. Tectonic thinning and extension in one place has been compensated by the formation of adjacent zones of tectonic thickening and folding about approximately E.–W. axes ; the folds indicate no consistent direction of translation.

Schmidt (1932) has described triaxial deformation in which extension occurs along the strike (parallel to the regional fold-axis) during deformation. Strand (1944) used this hypothesis to explain " cross folds " in the Bygdin area of Norway. Balk (1952) discussed elongation of a rock mass perpendicular to the direction of tectonic transport and has drawn an analogy between this phenomenon and the rolling process in metal working. The deformation was triaxial (three dimensional) and Balk suggests that rolling, with consequent elongation, also occurs in thrust zones. The phenomena described by

these workers closely accord with the present results from the Moine Thrust Zone.

Manifestly, the thrust zone within the areas examined represents a great movement zone, sometimes more than a mile thick, within which the Torridonian, Lewisian, and Moine rocks have undergone intense penetrative deformation about E.–W. axes resulting in the formation of E.–W. lineations and folding : the style of this deformation is flow and restricted transport perpendicular to the main direction of translation on the thrust planes. Restricted transport probably operated within the thrust zone during the main phase of transport on the thrusts, when the rocks were at a relatively deep tectonic level where the main compression could not find upward and outward relief.

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REVIEWS

MECHANIK DER ERDE. By R. A. SONDER. vii + 291 pp. with 91 blackline figures and 18 tables. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 1956. Price DM. 42.

With a sub-title " Elemente und Studien zur tektonischen Erdgeschichte " this is an ambitious study ranging over many of the most fascinating and fundamental problems of geology. If some new light were thrown on a few of the intriguing and often obscure topics listed this would be a massive contribution to geological thought.

The book is arranged in two parts. The first is a review of important tectonic data and processes. The processes classified thus—orogenic, epeirogenic, rhegmagenic, taphrogenic, phorogenic, and pyrogenic—are described against a background of geological time cycles and the structure and origin of the continents and oceans in relation to the structure of the Earth. The second part deals with theoretical geomechanics under broad heads including mechanical properties of the crust, tangential pressure, undation, tectonic potential, and contraction. In both parts the author favours systematic patterns whether of the timing of earth movements, or the distribution of crustal features; and he is skilful in schematizing them. This influences to some extent the rich selection of sources drawn upon and the author's readiness to coin his own terms where necessary.

The treatment as a whole is theoretical and often quantitative. The lack of empirical evidence will frustrate the reader who is using this book as a solution to fundamental problems, or as a survey of present knowledge. However, in a field, which, at the best of times, is flooded with tenuous speculation, we are given an eclectic concentration of schemata; and the reviewer has found it stimulating to contemplate in such a short space so many categories of geological thought.

W. B. H.

BEITRÄGE ZUR KENNTNIS DES KAMBRIUMS IN DER SALT RANGE (PAKISTAN). By O. H. SCHINDEWOLF and A. SEILACHER. Abhandl. der Math.-Naturwiss. Klasse, Jahrg. 1955, no. 10 (Akademie der Wissenschaften und der Literatur in Mainz, 1955). 190 pp. with 36 text-figs. and 33 plates. Price DM. 28.00.

This well-illustrated and important work falls into three main sections : a redescription of the fauna of the Salt Range Cambrian, a description of tracks and " ichnofossils ", and a discussion of the age of the Saline Series. The fauna is not large—in fact, it comprises less than a dozen species —but is fully described in 58 pages and illustrated in 10 of the 33 collotype plates. Apart from *Pseudotheca* cf. *subrugosa* and *Hyolithes wynnei* described under the heading Mollusca, it is entirely trilobite and brachiopod. The authors agree with W. B. R. King that in the Cambrian of the Salt Range only one species of *Redlichia* occurs, which cannot be further subdivided ; and they give a detailed redescription of this, the type species, *R. noetlingi*. As a result, Hupé's recently-proposed classification of the Redlichoids comes in for criticism. Among the brachiopods, the material of *Neobolus* in particular allows some detailed description supplemented by serial sections, and a full account is given also of the genus *Botsfordia* on the basis of *B. granulata*. A second equally large part of the volume is devoted to a discussion of tracks and burrows of various kinds, of which the Cambrian has yielded a surprising variety. Many of these have been plausibly related to trilobites, but other " ichnofossils " remain more uncertain. The very full description of these, with three-dimensional restorations, are of considerable interest, and are perhaps unexpected in a work with this title. In the third section, the authors conclude that the supposedly Tertiary microfauna and microflora is a result of contamination, and favour a Cambrian or possibly Pre-Cambrian age for the Saline Series.

O. M. B. B.

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SERGE LELIAVSKY. *An Introduction to Fluvial Hydraulics.* Constable and Co., Ltd., London, 1955. pp. xii + 257, with 88 text-figs. Price 30*s.*

G. M. DAVIES. *The Dorset Coast.* A Geological Guide. Adam and Charles Black, London, 1956 (Second Edition). pp. vii + 128, with 33 text-figs. and 7 plates. Price 9*s.* 6*d.*

The Penguin Atlas of the World. Penguin Books, Ltd., 1956. pp. xiv + 76, with 80 pp. of maps in full colour, and Index with 15,000 entries. Price 10*s.*

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THE LIVERPOOL AND MANCHESTER GEOLOGICAL JOURNAL. Vol. I, Part 4, 1954 (1956). Papers by P. G. H. Boswell, R. M. C. Eagar, J. E. Gillott, R. Kay Gresswell, J. C. Harper, D. Magraw, R. M. Shackleton, and J. Selwyn Turner. pp. 326–419 + xxiv–xxxvi, pls. 26–35. Price 15*s.*

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BRITISH TERRITORIES IN BORNEO. Geological Survey Annual Report, 1955. By F. W. ROE. Government Printing Office, Sarawak, 1956. pp. 241, 41 figs and 50 photographs. Price 7*s.*

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JUGOSLAVIA. *Société Serbe de Géologie.* Compte Rendu pour l'année 1954. Belgrade, 1956, pp. 137.

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Further particulars and information as to the method of application may be obtained from the Secretary, Association of Universities of the British Commonwealth, 36 Gordon Square, London, W.C. 1.

The closing date for the receipt of applications, in Australia and London, is *25th August, 1956.*

VICTORIA UNIVERSITY COLLEGE

Wellington, New Zealand

The Council of Victoria University College proposes shortly to appoint a LECTURER IN THE DEPARTMENT OF GEOLOGY, and invites application from suitably qualified persons for this post.

The salary will be £985 per annum, rising by annual increments of £50 to £1,235. The initial salary will be determined according to the qualifications and experience of the appointee. An allowance is made towards travelling expenses.

The successful applicant would be expected to take up his duties on the 1st February, 1957, or at such earlier or later date as may be agreed upon by the College Council.

Further particulars and information as to the method of application may be obtained from the Secretary, Association of Universities of the British Commonwealth, 36 Gordon Square, London, W.C. 1.

The closing date for the receipt of applications, in New Zealand and London, is *31st August, 1956.*

UNIVERSITY OF CAPE TOWN

South Africa

Applications are invited for the CHAIR OF MINERALOGY AND GEOLOGY.

The salary scale is £1,600 × £100 — £1,950. There is also a temporary cost of living allowance for a married man (at present £234 per annum).

Applications (with copies of testimonials) should state age, qualifications, experience and research work completed or in progress and give the names of two referees whom the University may consult. Two copies of the application and testimonials should reach the Secretary, Association of Universities of the British Commonwealth, 36 Gordon Square, London, W.C. 1 (from whom memoranda giving the general conditions of appointment and further information about the work of the department should be obtained) not later than *31st August, 1956.* An additional copy should be sent direct by air mail to the Registrar, University of Cape Town, Private Bag, Rondebosch, Cape Town, South Africa, by the same date.

The University reserves the right to appoint a person other than one of the applicants or to make no appointment.

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